P. SINGLETON.

Notes on temperature measurement

NOTES ON TEMPERATURE MEASUREMENT

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FOREWORD

IT is now over fifty years since the Foster Instrument Company first commenced manufacturing instruments for the accurate measurement of temperature. Having specialized almost exclusively upon this particular field of measurement since these early days, we have accumulated a wealth of experience which we are able to place at the disposal of our customers for the solution of the many problems in connection with temperature measurement and control which are so frequently encountered in industrial and research work. Our technical staff, many of whom are specialists in a particular branch of measurement, are at your disposal, and a service organization covers the whole of the country to ensure that the efficient working and accuracy of our equipment is maintained.

These technical notes on temperature measurement are largely based on our past experience and we trust that they will be of material assistance in helping our customers to understand some of the problems involved. It is hoped that these notes will be passed on to the personnel responsible for the operation and maintenance of our equipment.

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THE IMPORTANCE OF TEMPERATURE MEASUREMENT

The primary object of these notes is to illustrate some of the methods by which temperatures are measured and to discuss the basic principles and precautions to be taken to ensure accuracy and reliable service from an installation. It will not be out of place, however, to mention here how important is the question of temperature to man's economic progress, his physical comfort and even his very existence.

Almost without exception, every article produced under modern industrial conditions requires measurement and close control of the temperatures of the innumerable processes through which it must pass from the raw material to the finished product. It is true that many processes can be carried out at widely varying temperatures yet still result in an acceptable final product. There is, even so, always an optimum temperature for every process which will ensure either a better product, faster production, or the maximum economy of energy consumption. Furthermore, the efficient running and often the working life of an industrial plant is very largely influenced by the temperature at which it operates. Abnormal temperatures can even lead to dangerous conditions.

The present high cost of all forms of energy, whether solid or liquid fuel, gas or electrical power, calls for greater efficiency in consumption; the greater stresses imposed today on materials used in engineering require the best physical qualities of these materials to be developed; the high capital cost and replacement of manufacturing plant demands the longest efficient working life from it. These requirements and many others can be met by knowing and maintaining the temperatures at an optimum value, and it can be said truthfully that expenditure on instruments to accurately measure and control these temperatures will be saved many times over during their working life.

MEASUREMENT OF TEMPERATURES

GENERAL

Because temperature is a degree of intensity and not one of mass or substance, it cannot be measured directly as can units of length or weight. The problem is, therefore, much different from other forms of measurement and must be solved by observing the effects which temperature changes have upon different substances. It is only very rarely that such changes are observable in an accurately measurable form in the actual substance of which the temperature is required to be known. It is a fundamental condition that whatever is used as a means of measuring the temperature must be at the same temperature as the substance being measured. The non-attainment of this condition is probably one of the most frequent causes of inaccuracy in temperature measurement. It is very sound policy, therefore, with any installation to call upon the wide experience of the pyrometer manufacturers for advice in this connection.

Complete thermal equilibrium can seldom be obtained under industrial conditions and frequently different temperature readings may be obtained according to the method of measurement employed. Indeed there are a few applications where accurate measurement of temperature cannot be made for routine production work because of the impossibility of obtaining thermal equilibrium. With the advancement in instrument technology, new materials and improvement in design, satisfactory solutions to many of these problems are constantly being developed.

METHODS OF MEASUREMENT

The space available here does not permit describing all the various methods available for measurement of temperature, and these notes are therefore confined to the types manufactured by this company. Specializing almost exclusively upon instruments for temperature measurement and control, the Foster Instrument Company have concentrated upon electrical methods of measurement. The range covers the entire field from sub-zero to the highest temperatures encountered in industry or research, and comprises the following types.

Electrical resistance thermometers
Range : minus 240°C. to 550°C.

Thermo-electric pyrometers
Range : minus 200°C. to 1600°C.

Total radiation pyrometers
Range : 500°C. to 2000°C.

Optical disappearing filament type pyrometers
Range : 700°C. to 3000°C.

The thermo-electric type has by far the most extensive field of application and for this reason has been put first in the technical notes on the theory and operation of our range of equipments given on the following pages. We trust that these notes will be of interest and material assistance with regard to the efficient working and maintenance of our equipment.

THERMO-ELECTRIC PYROMETERS

The range of temperatures covered by thermo-electric pyrometers is normally between 300°C. and 1600°C., but in special cases temperatures down to 100°C. and sub-zero temperatures between minus 50°C. and minus 200°C. may be measured where conditions would preclude the use of any other type of measuring element.

A thermo-electric pyrometer functions by virtue of the small electric current generated by the heating of the junction of two dissimilar metals or alloys and is known as a thermocouple.

THEORY OF THE THERMOCOUPLE

Two dissimilar metals or metallic alloys joined together at each end (as shown at "A" on Fig. 1) will develop an electrical potential if a difference in temperature exists between the two junctions. The magnitude of the electromotive force (e.m.f.) generated depends upon:

(1) The composition of the two elements comprising the thermocouple.

(2) The temperature difference between the hot and the cold junctions.

If one junction is maintained at a constant and known temperature and the characteristics of the thermocouple element are known, the magnitude of the e.m.f. generated can be used as a measure of the temperature of the other junction.

CHOICE OF THERMOCOUPLE MATERIALS

While a very large number of different combinations of metals and alloys will generate a thermal e.m.f., for industrial purposes practical considerations limit the choice to some six different combinations. The metals must be stable under the conditions to which they are subjected, the e.m.f. generated must be of sufficient magnitude to be measurable under industrial conditions and should be consistent over the whole temperature range.

The following schedule gives briefly the characteristics of the types of thermocouple in most common use for industrial purposes and research work.

Positive element	Negative element	Maximum temperature		NOTES
		Continuous °C.	Intermittent °C.	
Copper	Constantan	400	500	Used mainly at low temperatures for laboratory and research work.
Chromel	Constantan	700	1000	Generates a higher e.m.f. for a given temperature than the other types, therefore used for low temperatures.
Iron	Constantan	900	1100	Iron element liable to rapid deterioration due to scaling when used at high temperatures in oxidizing atmosphere.
Nickel/ Chromium	Nickel/ Aluminium	1100	1300	Susceptible to attack by carbon, sulphur and cyanide fumes. Better in oxidizing than in highly reducing atmosphere.
Platinum-Rhodium Alloy	Pure Platinum	1400	1600	Must be protected against attack by metallic vapours and furnace gases; e.m.f. generated is very low, and requires a very sensitive indicating instrument.

More comprehensive notes regarding the characteristics, use and limitations of the different types of thermocouples are given on pages 13 to 17.

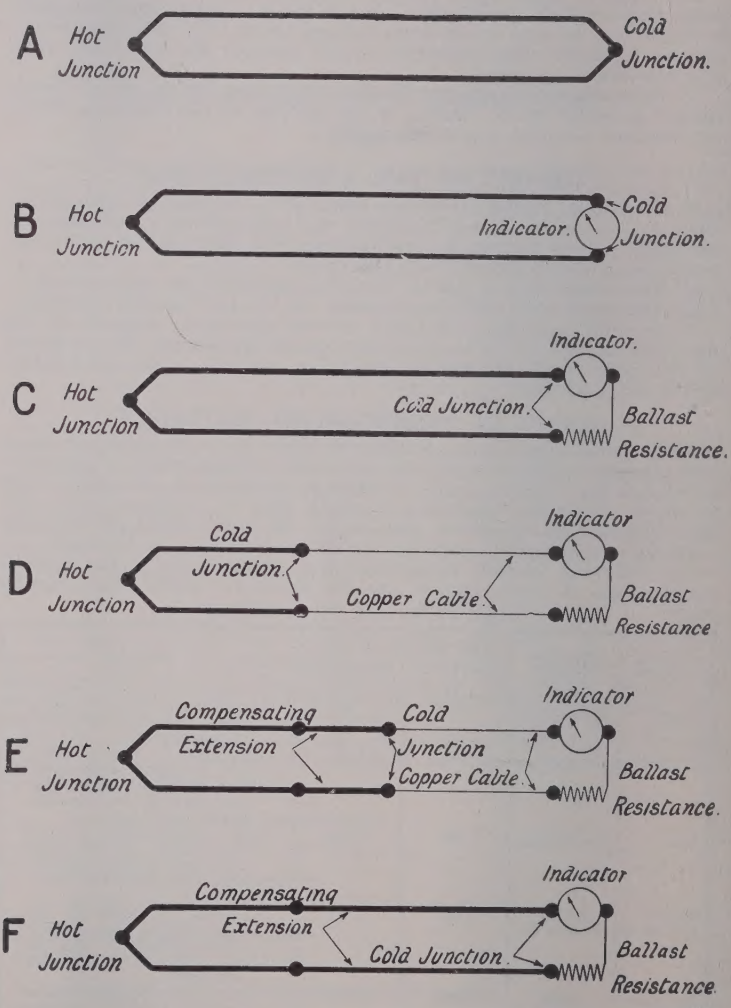

Fig. 1. *Development of the thermo-electric circuit.*

DEVELOPMENT OF THE THERMOCOUPLE CIRCUIT

In the simple form of thermocouple circuit, as shown at "A" on Fig. 1, a current will flow in the circuit due to the e.m.f. generated, but there will be no exterior indication of this. If a sensitive moving-coil type of galvanometer is connected in the circuit, as shown at "B," the presence of this current and a measure of its magnitude will be shown by the deflection of the galvanometer needle. With the arrangement shown, the actual "cold junction" of the thermocouple is now at the galvanometer terminals, and such apparatus could be calibrated as a pyrometer to read the temperature at the hot junction.

This arrangement will not, however, be entirely satisfactory. The current flowing into the circuit due to the e.m.f. generated at any particular temperature, and indicated by the degree of deflection of the galvanometer needle, will have a fixed value provided that the electrical resistance of the complete circuit, including the thermocouple and the galvanometer, remains constant.

It is not possible in an industrial application to realize such a condition. The moving coil of the galvanometer is wound with copper wire, the resistance of which varies with changes in temperature; moreover, the thermocouple itself over some part of its length will be raised to a high temperature, which will also cause a change in its resistance.

It is necessary, therefore, to modify the circuit as shown at "C" by introducing an additional "ballast," or "swamp" resistance, as it is sometimes known, made of a material the resistance of which does not change with change in temperature. This resistance should be of a value sufficiently high in relation to the resistance of the remainder of the circuit that any variations due to a change in temperature are a relatively small percentage of the whole. It is desirable in practice for the ballast resistance to be at least four times the resistance of the galvanometer moving coil.

The inclusion of this high resistance considerably reduces the value of the current for deflecting the movement of the galvanometer. The galvanometer must, therefore, be extremely sensitive and care must be taken in the design to avoid the possibility of errors due to friction between the finely pointed pivots carrying the moving coil and the jewelled bearings. Particulars and illustrations are given on page 28 of the "Resilia" method of resilient mounting of the moving coil to avoid damage to the delicate pivots by vibration and rough usage.

As stated in paragraph one, the magnitude of the e.m.f. generated for any particular thermocouple depends upon the difference in temperature between the hot junction and the cold junction. It follows, therefore, that if the instrument is to indicate the true temperature at the hot junction, the cold junction must be maintained at a constant temperature. Any change in the temperature at the cold junction will alter the magnitude of the e.m.f. generated, although no change in temperature at the hot junction has occurred. It is essential, therefore, that the cold junction must either be maintained at a constant temperature, at which the instrument was originally calibrated, or a correction made for any variations in the temperature of the cold junction.

METHODS OF COLD JUNCTION CORRECTION

It is customary (in this country) for pyrometers to be calibrated on the basis of the cold junction of the thermocouple being at the temperature of melting ice (0°C.) and for the instrument scale reading to start at this figure. If the cold junction is kept immersed in a flask of melting ice the instrument will then indicate correctly the temperature of the hot junction. This method of maintaining the cold junction at a constant temperature in melting ice is sometimes used for laboratory work, but is generally inconvenient for routine industrial work.

ARITHMETICAL CORRECTION

The base metal thermocouples supplied by this company as listed on page 7 have almost linear temperature/e.m.f. characteristics, i.e. the e.m.f. generated per degree of temperature is practically the same at all temperatures. It is possible, therefore, to make an arithmetical correction by adding the cold junction temperature above 0°C. to the observed reading of the indicator, which will give the correct temperature with sufficient accuracy for most industrial purposes. This does not apply to rare metal thermocouples, as the calibration curve of a platinum/rhodium thermocouple is not linear, the e.m.f. generated per degree of temperature below 100°C. being approximately only half that generated at temperatures over 800°C. The correction necessary for the cold junction temperatures for an instrument using a platinum/rhodium thermocouple is to add half the temperature of the cold junction above 0°C. to the observed reading.

This method of correction is inconvenient and it is unreasonable to expect an operator working under factory conditions to do mental arithmetic in order to ascertain the true temperature of his furnace. Fortunately it is possible to make the scale of the instrument direct reading in true temperature as explained below.

CORRECTION BY ZERO SETTING

The cold junction is maintained at a steady temperature, for instance 0°C. (32°F.), and, before connecting the thermocouple to the indicator, the indicator pointer is at the zero or lowest position on the scale and that position is marked 0°C. The hot junction is then heated to a steady known temperature, say, 100°C., the scale then being marked "100" at the position taken up by the pointer ; similarly, the hot junction may be heated to 200°C. and the scale marked correspondingly, and this process may be carried on up to the maximum reading of the scale, maintaining the cold junction all the time at 0°C. (it is sometimes convenient to leave out the "0s," specifying the scale as "hundreds centigrade" and figuring the calibration points 1, 2, 3 and so on). By this method of calibration, each successive step in the scale has been divided according to the current proportional to that difference of temperature—for instance, the width of scale between "100" and "200" is proportional to the current which would flow if the cold junction were at 100°C. and the hot junction at 200°C., and so on all up the scale.

Following the explanation above it will be evident that if the hot junction were maintained at, say, 300°C., and the cold junction, which had been previously at 0°C., were allowed to heat up to 10°C., there would be less current flowing because there would be less difference in temperature between the hot junction and the cold junction, although the hot junction has remained at a steady temperature. This difference in current would be represented on the scale by the distance from "0" to "10," so that if we disconnect the thermocouple from the indicator and set the pointer at 10°C., on reconnecting the indicator will read correctly the temperature of the hot junction because we have added on the scale the amount which we lost by the rise in temperature of the cold junction from 0° to 10°.

Similar results will follow for any particular temperatures of the cold and hot junctions ; provided the pointer is set to the actual cold junction temperature before the indicator is connected to the thermocouple, the pointer will then always indicate the true temperature of the hot junction. This method of setting the pointer is simpler and less liable to error than the method of making an arithmetical correction to the observed reading.

Any deviations of the room temperature from this setting will, of course, affect the accuracy of the reading, but if the normal ambient temperature fluctuations are not very great the indications may be sufficiently accurate for many industrial purposes. Where the ambient temperature of the cold junction is liable to rapid and extensive fluctuations, it is necessary to

provide means either to maintain the cold junction at a constant temperature or to automatically reset the zero of the instrument according to the changes in the ambient temperature.

The following methods are employed to maintain the cold junction at a stable temperature:

(1) VACUUM FLASK. The cold junction is immersed in oil in a vacuum flask, a mercury thermometer passing through the cork of the flask to read the temperatures of the oil by which to set the instrument zero. This method is mainly used for laboratory work.

(2) BURIED COLD JUNCTION. At four to six feet below the ground surface the temperature remains very constant. An iron pipe is usually driven into the ground at a convenient point and the compensating cables are led to the bottom of this and thence connected to the instrument with twin copper cable.

(3) THERMOSTATIC COLD JUNCTION BOX. The cold junction of the compensating cable is situated in a heat-insulated case provided with a thermostatically controlled heater which maintains the inside of the case at a constant temperature slightly above the highest ambient temperature which is likely to be experienced. The cold junctions of several thermocouples can be located in one cold junction box.

AUTOMATIC COLD JUNCTION COMPENSATION

To avoid the necessity of having to alter the zero setting whenever the temperature of the cold junction changes, instruments may be fitted with an automatic cold junction compensation device which varies the zero setting of the instrument according to the changes in temperature. This device consists of a temperature-sensitive bi-metallic spiral to which one end of the indicator movement control spring is attached. The bi-metallic spiral is calibrated so that the pointer is moved over the scale in exact relation to the changes in the ambient temperature at the instrument.

All Foster instruments fitted with automatic cold junction compensation are provided with a thermometer pocket to enable the temperature inside the case adjacent to the compensating device to be measured by a mercury thermometer in order to check periodically the zero setting.

Returning again to the diagram on page 8 showing the development of the thermocouple circuit, it will be seen that the arrangement shown at C assumes that the thermocouple will be extended right up to the indicator terminals. This is possible in laboratory work or on very small industrial furnaces, but for most industrial work it is not convenient to make the thermocouple sufficiently long for this purpose, and therefore connection between the thermocouple and the indicator may be made by means of insulated copper cables as shown at "D."

In this case the cold junction reference temperature to which the indicator zero must be set is the temperature at the junction between the thermocouple and the copper cable. It will be appreciated that the cold junction in close proximity to a furnace wall may be subjected to high and fluctuating temperature and that in consequence serious inaccuracies will occur in the indicated temperatures.

COMPENSATING CABLES

The cold junction must, therefore, be brought to a position where it will remain at a reasonably constant temperature. Flexible cables having the same thermo-electric characteristics as the thermocouple are therefore used to extend the thermocouple to a point where a stable temperature is maintained. These cables, known as compensating cables, are not necessarily of

the same material as the thermocouple itself, but are such that the characteristics are the same between 0°C. and 100°C. If the compensating cable is extended to a position where a reasonably cool and stable temperature exists, the remainder of the circuit may be completed in insulated copper cable, in accordance with the arrangement shown at E. The cold junction reference temperature is now at the junction between the compensating cable and the copper cable, and it is the temperature at this point which must be used for setting the instrument pointer for the zero.

Copper cable is less expensive than compensating cable and also the electrical resistance is much lower. Where the distance between the thermocouple and the instrument is very great, the arrangement shown at E has advantages both by reason of lower cost and reduced resistance of the circuit. The influence of circuit resistance on the performance of a pyrometer is discussed on pages 18 to 22.

Where an instrument is fitted with automatic cold junction compensation as already described, the automatic setting of the zero adjustment to compensate for changes at the cold junction temperature is governed by the temperature inside the instrument. In such cases the compensating cable must terminate inside the instrument as shown at F, so that the cold junction is at the same temperature as the automatic cold junction compensating device.

As it is usually more convenient to measure the cold junction temperature at the instrument itself it is now the usual practice for the compensating cables to be brought right up to the instrument, even where automatic cold junction compensation is not employed.

IMPORTANT. As already pointed out, compensating cables are not necessarily of the same material as the thermocouple wires and the thermoelectrical characteristics are only the same for temperatures up to 100°C. It is essential therefore to ensure that the temperature at the junction between the thermocouple wires and the compensating extension is always less than 100°C., otherwise serious errors in the indicated temperature will result, and, moreover, there is danger of trouble occurring due to deterioration of the insulation of the cable at high temperatures. When deciding the overall length of thermocouple and protecting sheaths required it should always be borne in mind that it should protrude sufficiently from the furnace casing to ensure that the connector head will never reach a temperature approaching 100°C. Proximity to flues and the effect of radiated heat from furnace openings should be taken into account and if necessary the connector head should be shielded from these effects or an angle type thermocouple used to avoid trouble in this direction.

CHOICE OF THERMOCOUPLES AND SHEATHS

The materials available for the construction of thermocouples fall into two classes:

(1) **Rare metals,** which include mainly pure platinum and alloys of platinum and rhodium or platinum and iridium.

(2) **Base metals,** which include mainly iron, copper and alloys of copper-nickel, nickel-chrome and nickel-aluminium.

The primary consideration which determines the suitability of thermocouple material is the maximum temperature to which it is to be subjected, but it is also important that operating conditions should not cause any physical or chemical change in the composition of the the mocouple. Such changes will either seriously affect the constancy of the e.m.f. generated or, at least, lead to their early destruction. Little trouble arises when temperatures are comparatively low, say below 500°C., but the problem becomes increasingly difficult as the temperature increases above this figure.

In considering the possible effects of high temperature upon the thermocouple alloys, their melting point is the first quality which comes in view.

It is obvious that the melting point of the thermocouple must be above the maximum temperature to be measured. Unfortunately, in many metals which have a very high melting point, there are other defects which set a limit to the maximum temperature to which they can be heated. In some cases oxidization is the cause of destruction, while in other cases contamination by gases and metal vapours is the more serious consideration.

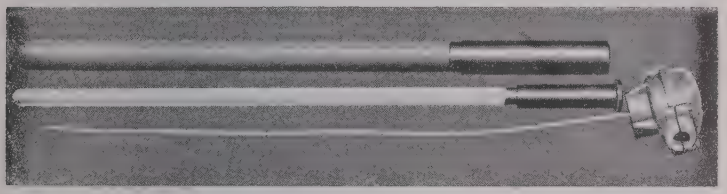

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Fig. 2. *Rare metal thermocouple with inner and outer protecting sheaths and connecting head.*

RARE METAL THERMOCOUPLES

Where very high temperatures have to be measured, and where the conditions of use indicate the thermocouple as the desirable type of pyrometer, platinum and its alloys usually provide the best type of thermocouple. The two best known rare metal thermocouples employ one wire of pure platinum, the other wire being an alloy of platinum and rhodium or of platinum and iridium. These metals do not oxidize seriously, even at temperatures approaching their melting points. When used at a temperature above 1000°C. (1832°F.) the contaminating effects of reducing gases and metal vapours tend to destroy the mechanical strength and to alter the electrical calibration, but when suitable protection can be given and conditions otherwise favourable can be secured, as, for instance, in many laboratory experiments, it is possible to use the platinum v. platinum-rhodium thermocouple up to temperatures as high as 1700°C.

With the platinum v. platinum-iridium couple volatilization of the iridium and consequent contamination of the pure platinum prevent satisfactory use of this thermocouple at temperatures over 1000°C. (1832°F.).

These rare metals being expensive, only small diameter wires may be used on the score of economy; 0.5mm. (1/50th inch) diameter being the size usually employed. Such fine wires are not mechanically robust, and furthermore the electrical resistance is high.

Platinum also has a high temperature/resistance co-efficient, so that the resistance when cold increases very considerably when the thermocouple is raised to a high temperature. The electromotive force is very small—for instance, a thermocouple having one wire of platinum and the other wire of 90% platinum and 10% rhodium develops an electromotive force of about one-hundredth of a volt (10 millivolts) when the temperature is about 1000°C. (1832°F.) and the cold junction at 0°C. (32°F.).

As explained earlier, it is necessary to introduce into the circuit an additional or "ballast" resistance, which is usually incorporated in the indicator or recorder. Because of the considerable increase in the resistance of a platinum thermocouple when it is raised to a high temperature, it is obvious that the ballast resistance in the circuit must also be very large in order that these changes in resistance shall have no material effect. Any considerable fractional change in the resistance of the circuit would make a proportionate change in the current flowing for any given temperature difference between the hot and cold junctions of the thermocouple.

It results, therefore, that the whole electrical circuit in connection with the platinum v. platinum-rhodium thermocouple must be of high resistance, usually more than 100 ohms; therefore it will be clear that the current flowing in the circuit is extremely small. The force tending to move the indicator pointer is, therefore, also extremely small, because it depends upon the current flowing in the circuit. In the case mentioned above, for a temperature of 1000°C. (1832°F.), an electromotive force of 10 millivolts acting in a circuit of 100 ohms results in a current flowing in the circuit of only one ten-thousandth of an ampere (0.1 milliampere). This point is discussed more fully on page 21.

The current being so extremely small complicates the problem of making a robust indicating millivoltmeter for use with rare metal thermocouples. Notes regarding the design and construction of the "Resilia" movement are given on pages 26 and 28 and particular note should be made regarding the merits of "high torque" versus "high resistance" movements. We would like to point out here that the "Resilia" movement is designed primarily for temperature measurement and not adapted from a purely electrical instrument. Each movement is designed to suit the particular application for which it is to be used; the winding data for a coil for use with a rare metal thermocouple being altogether different from that suitable for a base metal couple. This, together with the "Resilia" method of mounting the moving coil, is probably one of the main reasons for the outstanding reliability of the Foster pyrometer.

PROTECTING SHEATHS

Rare metal thermocouples are very susceptible to attack by furnace gases at temperatures exceeding 1000°C. Even short exposure will cause contamination which seriously alters the temperature/e.m.f. characteristics and eventually leads to the total destruction of the couple. It is essential therefore for adequate protection to be given against access by the products of combustion. Metallic sheaths alone are completely unsuitable as these emit metal vapour at high temperatures which will contaminate the platinum and cause rapid failure.

Of the non-metallic materials, the three which seem to promise the best success are a high grade of porcelain glazed externally, a close-grained compound of fireclay or other refractory substance with a binder, and fused silica. These are discussed in that order below. Good porcelain is itself highly resistant to temperature, but in the "biscuit" form it is liable to be slightly porous to furnace gases, therefore it is necessary to discover a glaze, also highly resistant, which will seal the microscopic pores in the biscuit. Such a combination has been achieved but suffers from the very serious practical disadvantage that the material has a considerable co-efficient of expansion, yet is also very rigid. It follows naturally that any rapid change

in temperature will result in the cracking of the porcelain. Similarly, what is more embarrassing is the result of any steep temperature gradient, as, for instance, where the sheath projects from a fairly close-fitting hole in a furnace wall into the inner furnace space. The part inside the furnace space tries to expand because it is at a very high temperature while that within the wall is at a lower temperature and resists expansion, and a fracture is inevitable.

A partial cure for this trouble is found by using porcelain as an inner sheath and "blanketing" it with a thick outer sheath of fireclay. The fireclay, if of the right kind, is sufficiently refractory to withstand fairly high temperatures without fracture or distortion and smooths out temperature changes and temperature gradients in the inner porcelain sheath. The trouble with this arrangement is that, as the temperature rises, the fireclay outer sheath is liable to sag in the case of an insertion that is not vertical and thus to break the inner porcelain sheath, which is still quite rigid. Even with vertical insertion sometimes warping produces the same failure. If, by mechanical vibration, the porcelain sheath is broken while the outer fireclay sheath remains intact, the breakage is not visible by external inspection and therefore the thermocouple wires are left exposed to the contaminating gases which percolate through the porous fireclay sheath. Lastly, the use of an outer sheath reduces the promptness of indication in some cases to such an extent that one highly expert user has remarked that the pyrometer was "measuring the temperature of last week."

Taking the second alternative, carborundum has been suggested and used, and similar sheaths have been made with alundum and other highly refractory crystalline materials. These are not self-binding and therefore must have a binder to connect the crystals into a rigid sheath and the binder forms the weak link in the chain. If it is such that it becomes plastic at high temperatures, the sheath will tend to warp and sag, whereas if the binder is not plastic it will probably be porous and therefore the sheath would not protect the thermocouple from entry of deleterious gases. Until quite recent times all attempts to get over these particular difficulties have failed.

In the case of fused silica there is a great practical advantage for many cases in the fact that the material has an entirely negligible co-efficient of expansion and is therefore not liable to cracking with sudden change in temperature or steep temperature gradients along the length of the sheath. Sheaths of fused silica can be made quite thin so that they transmit the heat by conduction very quickly to the thermocouple wires; and, indeed, they have also the advantage of some degree of direct transmission because the material is transparent or translucent. As usual, there is a disadvantage, and in the case of this material it is that it tends to devitrify and return to its original crystalline or granular form when exposed for any length of time at temperatures at or above 1000°C. Once this devitrification has taken place the sheath can no longer be relied upon to exclude gases and it is extremely weak mechanically. It will be readily understood that, for these reasons, fused silica is mainly suitable for a protection sheath for short-period work and if that is at temperatures over 1000°C. frequent replacement will be necessary.

In the case of all three of the above materials, their very rigidity involves liability to mechanical fracture in the case of shock or vibration, they are brittle and must be handled with great care. There is a further trouble which may arise, more or less common to all three. Furnace gases often carry minute particles of ash and similar materials and these are probably in the form of molten globules when the gases are at a very high temperature. As the gases impinge upon the sheath the globules are deposited and they have a fluxing action upon the surface of the sheath. Further, and particularly with those sheaths having a glaze or binder, they may penetrate sufficiently into the surface to alter the co-efficient of expansion of the sheath in that part so that it is different from that on the opposite side of

the sheath. It will be readily conceived that warping or fracture is then the more liable to occur.

It cannot be claimed that, even at this present date, there is any ideal solution to these problems of producing a protection sheath, but very considerable technical advance has been made, so that now it is quite possible to choose a sheath which will give a reasonable life in normal industrial service, without necessitating very onerous conditions in the installation. The improvement was not achieved until investigators broke away from what may be termed the "laboratory complex" and visualized what was wanted for purely industrial purposes. The first point that emerged was that a breakaway must be achieved from the custom of scaling industrial indicating pyrometers for rare metal thermocouples up to 1600°C. This scheme originated largely on the Continent and is still persisted in, in some cases. In England the realization that the temperature above 1400°C. could not, in any case, be measured satisfactorily with thermocouples in industrial work is now fairly general, and therefore it was only necessary to search for a sheath whose material would remain rigid up to that lower maximum temperature.

The class of materials now found most satisfactory lies between the first two types previously described; they have a very close grain like biscuit porcelain and are of highly refractory material and the mixtures used are self-binding without a low-fluxing binder, and therefore remain rigid up to 1400°C. They are known under various trade names and different pyrometer manufacturers favour different makes, but if they are of this successful type they are broadly all similar. External glazing is not necessary because the material is to some extent internally vitrified or fluxed and therefore they are sufficiently impervious to furnace gases. No deleterious gases are given off by the sheath material and, lastly, they are more resistant to thermal shock or temperature gradients than porcelain, though they should not be subjected to extremes of this nature.

With these materials there is no need to use an outer sheath, and therefore the time-lag incidental to that device is avoided. Visual observation shows the condition of the single sheath and that furnishes an additional assurance for the user. Lastly, they do not readily suffer from the impinging of ash particles, which do not seem to adhere so readily to the surface as in the case of the other fireclay materials. It will be clear from the foregoing considerations of the sheaths that, in the case of rare metal couples, the fact that their melting point is over 1700°C. is really no help because the limit is set by what the sheath will stand.

BASE METAL THERMOCOUPLES

NICKEL/CHROMIUM v. NICKEL/ALUMINIUM

These alloys, known as "Chromel" and "Alumel" in America and "T_1" and "T_2" in Great Britain, are composed mainly of nickel, hence at first glance it would appear that they are suitable for temperature measurement to almost as high a temperature as those practicable with rare metal thermocouples. This is not the case, however, since all base metals when used continuously at elevated temperatures tend to oxidize rapidly. It is possible to use these base metals up to 1300°C. for very short periods. Indicators and recorders are frequently scaled to that maximum and couples in such short-period service have the advantage that the base metals, being relatively cheap, can be in the form of thick wires and hence mechanically stronger than the rare metals. For continuous work it is better to regard 1100°C. as the maximum when, with the protection of a suitable sheath, the effective life of the thermocouple can be reasonably long and the cost of renewal is low compared with the cost of renewing rare metal thermocouples.

With these, we again come to the problem of a suitable sheath, but the conditions required are less onerous than for the rare metals. Although metal vapours do not appear to have any deleterious effect upon the wires, nickel/chromium-nickel/aluminium thermocouples contain a high percentage of nickel, which is very susceptible to attack by sulphur compounds in the products of combustion and also to very highly reducing furnace atmospheres.

On the other hand, nickel/chromium-nickel/aluminium forms a very tenacious oxide film on its surface. This oxide film is not absorbed by the metal and this protects the wires against further oxidization. They are, therefore, more satisfactory in oxidizing or neutral atmospheres.

With oil-fired furnaces in which a large proportion of sulphur is present, with towns' or producer gas and also metallurgical furnaces using a reducing atmosphere, protection from the furnace gases must be provided for the thermocouple wires. For temperatures normally about 1000°C., and which may rise to 1100°C. or higher, no metal or alloy is suitable, and the sheath must therefore be of the fireclay nature. The particular compounds referred to as satisfactory for rare metals are equally successful for base metals at high temperatures. Where the temperatures to be measured never exceed 1000°C., and are normally at or below 900°C., alloys of nickel and chromium are valuable as sheaths. They are made in various degrees of purity and both in cast and wrought forms, each variety having characteristics suitable for particular service conditions, but the whole series has the definite advantage of slow oxidization, so that, although relatively costly, they are a good investment for the temperature ranges indicated.

Lower still in the temperature scale, sheaths of "calorized" steel give a fairly long life at a low first cost, while for work not exceeding 800°C. a sheath of common weldless steel may be used. This, although cheap, does not last long under oxidizing conditions, and in many services where the temperatures are low it is quite practicable to dispense altogether with the sheath, the response to temperature change being of course much more rapid.

IRON-CONSTANTAN

For temperatures not normally exceeding 900°C. it is often preferable, in place of the nickel/chromium-nickel/aluminium base metals in the form of wires, to use a thermocouple of concentric form, one element being in the form of a thick outer tube, the other a stout central rod, insulated in the length of the couple but welded together at the hot junction. Such a thermocouple is very strong mechanically and the only function required of the sheath, if any, is to reduce the rate of oxidization of the tubular element. For some classes of intermittent measurements, no sheath need be used even up to 800°C., yet the couple is mechanically strong and at the same time its response to temperature change is as rapid as a bare couple of the wire type.

From the foregoing explanations it will be clear that there is no single sheath which is universally preferable, and, in fact, each case should be studied individually before a correct selection can be made; the more complete the information as to the intended service, the better the chance of a correct solution to the sheath problem in the first installation. Allied with this matter of sheaths is the arrangement for attaching the sheath to the thermocouple or its connecting head and also the fitting into the furnace. All of these factors have a direct bearing upon the successful use, and on the life, of the pyrometer.

DEPTH OF INSERTION

Another matter to be considered when using a sheath is the depth of insertion, bearing in mind that a proportion of the heat received by the sheath will be lost by conduction along the wall of the sheath and will not reach the thermocouple. If the insertion is not deep enough, the pyrometer will tend to read low, because the actual "hot junction" of the thermocouple will never acquire the full temperature of the heated zone in which the sheath is inserted.

Taken by itself, this exposition would indicate that the deeper the insertion the better, and this is technically true. Against this conclusion is the fact that the cost of renewals of sheath and couple is greater when they are inserted more deeply and, in many cases, the sheath gets in the way of the work in the furnace. A midway course is the best, as is often the case in engineering problems. It should be noted that, in a furnace having walls of refractory material, the inner part of the wall will itself be at a high temperature and can therefore be counted as part of the effective depth of insertion.

As already indicated, the relatively low cost of the base metals allows the cross-section of the thermocouple to be large ; for instance, the standard for the industrial wire type thermocouple in base metal is 3mm. ($\frac{1}{8}$in). A further advantage, when the temperature range allows the use of the base metals, is that the electrical resistance of these thicker wires is low and, fortunately, the increase of that low resistance when the thermocouple is heated in the furnace is also very low. Lastly, the e.m.f. is much higher than with the rare metals, about four times that of the platinum v. platinum/rhodium thermocouples.

In this connection the chromel-constantan thermocouple generates the highest e.m.f. for a given temperature difference of all commercially used thermocouples and for this reason is to be preferred for low temperatures or sub-zero temperatures where the use of a resistance thermometer is precluded.

PYROMETER CIRCUIT RESISTANCE

DESIGN OF THE MOVING COIL INDICATOR

The following notes are specially directed to the thermo-electric (or thermocouple) type of pyrometer, but it may be mentioned that this type will include also the radiation pyrometer, in which the sensitive part is actually a very small thermocouple. As the matters discussed apply equally to indicators and recorders, the former term is to be understood as including also the latter.

The elementary thermo-electric pyrometer circuit which has already been illustrated in Fig. 1 on page 8 comprises the thermocouple, compensating extension and sensitive indicating or recording instrument. Fig. 3 shows diagrammatically the construction of a typical moving coil indicator movement.

A moving coil 4, carried on pivots 5-5, bearing in conical jewels 6-6, swings in the air gap between the pole pieces 1 and 2 and the central core 3. This air gap is crossed by a strong magnetic field provided by a permanent magnet, not shown in the illustration. Connection is made to the coil through the hair springs 7-7.

The moving coil tends to turn about its axis in the magnetic field under the influence of current flowing through it due to the e.m.f. generated by the thermocouple. This turning is restrained by the control springs 7-7, so that the deflection is a measure of the current flowing. A pointer attached to the moving coil will then indicate the amount of deflection against a scale which may be graduated directly in terms of temperature.

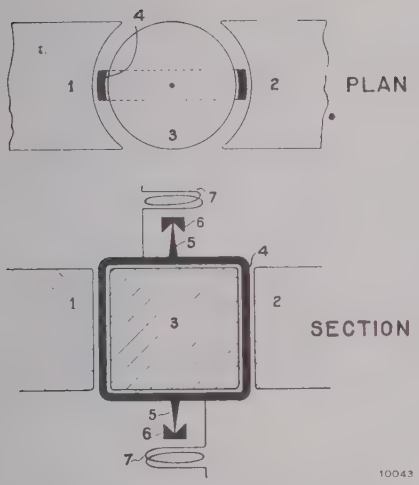


Fig. 3. *Diagram of indicator movement.*

The turning force, or torque, generated by the reaction between the magnetic field and the coil depends upon the strength of the magnetic field, the current flowing in the coil and the number of times the current passes round the coil (ampere-turns). For instance, with any given magnetic field, a current of one ampere passing four times round the coil will generate the same torque as a current of one-quarter of an ampere passing sixteen times round the coil ; in each case there will be four ampere-turns. The diagram in Fig. 4 shows how these two coils each have the same total cross-section, and are therefore the same weight. Many factors, in addition to considera-

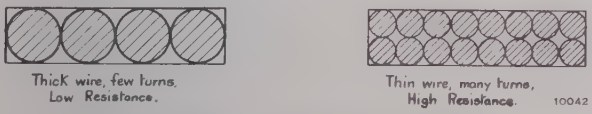


Fig. 4. *Diagram of cross-section of moving coil.*

tions of weight, size and cost, put fairly definite limits upon the strength of the magnetic field, and somewhat similarly the maximum allowable crushing stresses on the fine pivot points put limits to the size and weight of the moving coil, so that in practice these factors are more or less fixed and uniform in different designs of indicators. Consequently there remains as a possible variable the size of the wire used, and therefore the number of turns in the coil ; if finer wire is used there will be more turns.

But, as is usual in any engineering design, advantage in one direction is gained at the expense of loss in another direction. Wires of very small diameter offer a correspondingly high resistance to the passage of the current, so that although the number of turns may be increased by using finer wires, the current flowing will be decreased. With the example already taken above, a current of one ampere made four turns round the coil ; that is, there were four ampere-turns to generate the torque. If we reduce the diameter of the wires to one-half, the cross-section of each wire, and the

space it occupies, will be one-quarter ($\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$), and there will therefore be sixteen turns in the same cross-section of the coil and having the same total weight. But the electrical resistance of a wire varies inversely to its cross-section, therefore the resistance of each turn will be four times that of the single turn of thick wire and, since the current passes in succession through all the turns, the total resistance of the coil will be sixteen times as great ($4 \times 4 = 16$).

By Ohm's Law, the greater the resistance of the circuit the smaller the current flowing for any given e.m.f., so that for the same e.m.f. from the thermocouple the current will be only one-sixteenth of an ampere, and therefore there will only be one ampere-turn to generate the actuating torque ($\frac{1}{16} \times 16 = 1$); that is to say, the high resistance coil will generate only one-quarter of the torque generated by the low resistance coil. Although many other factors enter into the design, these only modify slightly the effect of using many turns of fine wire, and the examples taken above show the broad conclusion that the higher the resistance of the moving coil the smaller the torque available for a given e.m.f., and therefore, because the e.m.f. depends on the temperature, for a given temperature measurement. Trials show that the maximum torque is achieved when the resistance of the moving coil equals the sum of all the other resistances in the circuit, that is the resistances of the thermocouple, compensating extension, copper cable, springs and ballast.

Unfortunately, such ideal proportions of the moving coil and other resistances are not possible for reasons which are elaborated below, but it should still be borne in mind that, provided the other elements of design are duly considered and the various resistances in the circuit are properly proportioned, low coil resistance and large currents secure the greatest robustness in service.

In order that the resistance of the moving coil may be kept as low as possible, pure copper and pure aluminium are the only metals which may be used economically. The electrical resistance of these pure metals increases with a rise in temperature, so that the resistance of the moving coil will vary with changes in temperature.

This effect is quite important because a rise of 10° in the temperature of the moving coil will cause an increase of 4 per cent in its resistance. It is stated above that the condition for maximum torque is achieved by making the moving coil equal to all the other resistances; that is to say, the coil should represent half the total circuit resistance. In such a case the rise of 10°C. will increase the total resistance by $4/2 = 2$ per cent. Therefore, since the e.m.f. depends on the temperature measured, the current will be 2 per cent less, thus the control springs will limit the turning of the coil to a greater extent and the actual temperature reading will be 2 per cent lower than the correct reading. Since a rise of 10°C. (18°F.) is quite probable between night and day, or due to other causes, the proportions of the circuit resistances resulting in such a drop in reading will not be allowable. It must also be remembered that if any copper cable is in the circuit, possibly in positions where it will experience even larger changes of temperature than 10°C., and although the cable will have a lower resistance than the moving coil, the effect of its change in resistance may well be added to that shown above, thus making the temperature error more than 2 per cent.

The resistance of constantan or Eureka wire does not change with temperature, and if a resistance of this material equal to twice the resistance of the moving coil is inserted in the circuit the resistance of the copper will then be only one-quarter of the total resistance. The temperature error for a rise of 10°C. will therefore be only 1 per cent. In practice this Eureka resistance is usually over four times the resistance of the copper in the moving coil, so that the temperature error is reduced to a negligible amount. Because the effect of this resistance coil is to steady the indications and

reduce variations, it is usually called the " ballast " resistance and is shown under that name in Fig. 1.

It should be noted that the conditions described above to secure low temperature error are only matters of proportion so far.

COMPARISON, HIGH & LOW RESISTANCE INSTRUMENTS

The two examples below would have the same small temperature error, assuming that the control springs do not vary their resistance with temperature, which is approximately true. It is also assumed in this example that the thermocouple remains at a fixed depth of insertion and therefore does not vary its resistance.

Approximately the same size of moving coil is taken in each case ; that is, a coil of thick wire having 40 turns, of total resistance 2.0 ohms, would be the same size and weight as one of thin wire of 160 turns and resistance 41 ohms, and the net result is that the low resistance instrument will have five times the ampere turns of the high resistance instrument.

$\left(\frac{0.08}{0.016} = 5\right)$ with equally low temperature error.

As explained in other paragraphs, the greater the ampere-turns generated in the moving coil the larger the controlling torque and the more robust the instrument.

Part of circuit	*Low resistance*	*High resistance*
Thermocouple	0.1 ohms	2.0 ohms
Compensating extension ...	0.1 ,,	2.0 ,,
Copper cable	0.3 ,,	5.0 ,,
Control springs	1.0 ,,	5.0 ,,
Copper moving coil ...	2.0 ,,	41.0 ,,
Ballast resistance	6.5 ,,	145.0 ,,
Total resistance ...	10.0 ,,	200.0 ,,
Proportion of copper to total resistance	$\frac{2.0 + 0.3}{10} = 0.23$	$\frac{41 + 5}{200} = 0.23$
Temperature error for rise of 10°C.	$4\% \times 0.23 = 0.92\%$	$4\% \times 0.23 = 0.92\%$
Assuming an e.m.f. of $\frac{20}{1000}$ volt, the current will be	$\frac{20}{1000} \div 10 = \frac{2}{1000}$ amp.	$\frac{20}{1000} \div 200 = \frac{0.1}{1000}$ amp.
With the same size of moving coil the number of turns will be*	40 turns	160 turns
Ampere-turns generating deflecting torque	$\frac{2}{1000} \times 40 = 0.080$ ampere-turn	$\frac{0.1}{1000} \times 160 = 0.016$ ampere-turn

* Allowing for the weight and space occupied by the insulation on the wire.

EXTERNAL CIRCUIT RESISTANCE

It will be seen from the foregoing that the high torque, low resistance instrument is to be preferred on the score of robustness. There are limitations, however, to the universal use of low resistance instruments because of possible variations in the circuit resistance. In the case of the two examples specified above, with the low resistance a change in the total circuit resistance of 0.1 ohm will cause a 1 per cent error in the instrument reading, while with the high resistance movement for the same percentage error a change in resistance of 2 ohms is permissible. Using a heavy

gauge base metal thermocouple of normal length and compensating extensions up to 20 feet the possible change in resistance will be negligible, and such an equipment in conjunction with a high torque, low resistance indicator will give very satisfactory results. It is very essential, however, that very sound electrical contact is always maintained at all connections in the circuit, and it is strongly recommended that soldered connections rather than dry mechanical contacts should be made wherever possible.

It has already been pointed out that the resistance of a rare metal thermocouple, initially very high, increases considerably when raised to a high temperature. Base metal thermocouples and compensating cables also increase in resistance when the temperature is raised, and this variation in resistance may be serious where very long thermocouples or compensating cable runs are used.

The foregoing remarks will suggest that, for each set of conditions, including type and length of couple, number, type and length of connections and the type of switch used, if any, there is an optimum resistance for the indicator or recorder which will represent the best all-round compromise between the conflicting factors of possible variation of reading and industrial robustness. Foster pyrometers are made and standardized in a wide range of sensitivities and resistances so that there is always a proved and tested pattern available closely approximating to that optimum, a matter of great advantage over the products of makers who standardize on one sensitivity and proportion of resistance because they must make that one pattern of the highest resistance they dare to produce, and it is unduly delicate for a large proportion of industrial applications.

PIVOTING SYSTEMS

In the early days of industrial pyrometry, the moving coil, carrying the pointer, was invariably suspended by a fine wire or strip, but nowadays such a system of suspension is usually discarded in favour of pointed pivots working in conical jewels. Since no pivoting system can be entirely free from friction effects, some examination of the different systems of pivot mounting will be of assistance to pyrometer users, not only to enable them to understand the problems which have to be surmounted by the instrument designer but also to help them to select the instrument most likely to survive the expected conditions of use in a condition giving the desired accuracy. Though, of course, the various factors are amenable to mathematical treatment, and, indeed, are calculated by the designer just as in the case of very much larger moving structures, mathematics are not essential to the user's understanding of the matter, and all formulæ have therefore been rigidly excluded from this description.

DIRECT DEFLECTION PYROMETERS

In pyrometers of the direct deflection type the excursions of the pointer or recording arm measure the amount of current flowing and, by suitable calibration, the actual temperature. Since the moving coil and its mounting is essentially the same whether the instrument is recording or simply indicating, the indicator only need be discussed, and that instrument will stand also for the recorder. But before leaving the recorder, one peculiarity of that instrument having a direct connection with its pivoting should be noticed. As will become evident from the succeeding explanations, the forces available to turn the recording arm are far too small to move a pen continuously in contact with a chart ; it is, therefore, always necessary, with direct deflection recorders, to use a quasi-continuous method of making the record, the recording arm being mainly free to take up its true deflection, but being periodically depressed to leave a "dot" upon the chart. Such periodic depressions cannot be applied without involving some additional forces upon the pivots, therefore any arrangement caculated to minimize damage due to pressure or shock is doubly valuable in a recorder.

MOVING COIL PYROMETERS

It is first necessary to emphasize the fact that the turning forces available, even with the most efficient design, are many times smaller than those developed in the moving-coil ammeter or voltmeter, instruments which are otherwise similar in that they operate by the reaction between a coil carrying a current and a magnetic field in which it turns causing the coil to rotate and thus to carry a pointer over a scale.

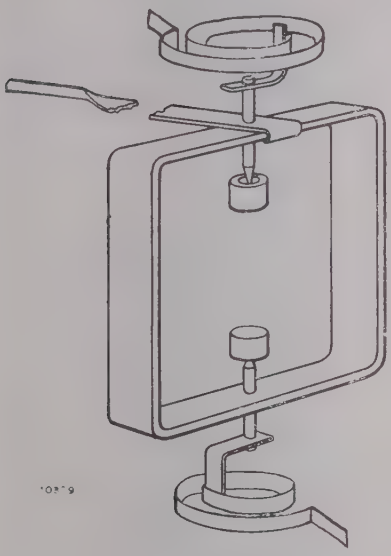


Fig. 5. *Moving coil system.*

In Fig. 5 a typical arrangement is shown, the coil turns in a radial magnetic field about the axis provided by the two in-turned pivots having their bearings in conical jewels. This turning is opposed by two spiral control springs above and below the coil, which also serve to lead the current into and away from the coil. In order to convey some concrete idea of the very small turning forces with which pyrometers have to work, one may imagine the smallest size of office pin hung by a fine silk thread. If such a minute weight—about 30 milligrammes—acted on a drum of 1 centrimetre radius, as shown in Fig. 6, that would represent the whole force available, in a high-sensitivity pyrometer indicator, to turn the pointer over the whole length of the scale. In an ammeter of good design, the forces would be anywhere from 10 to 30 times as large.

MINUTE TURNING FORCE

At first glance a torque of 30 milligramme-centimetres might be considered quite a fair working force, but that is not the whole story. This torque is the force necessary to produce a full-scale deflection, and that force is developed by the current in the moving coil. But it is balanced by the control springs, such as are shown diagrammatically in Fig. 5; therefore, at any given constant temperature, the turning force due to the current flowing will be balanced by the opposing torque of the control springs. Let this be at half the maximum scale. Then there will be a torque of 15 mg. cm., due to the current flowing, balanced by an exactly equal and opposite spring force, and the pointer will be at rest. Now assume that the temperature increases by 100th part of the full scale value, for instance 10° on a scale of 1000°C. Then the additional or unopposed force available to start the pointer from rest, and to move it up the scale to the new reading 10°C. higher, is 100th of that for the full-scale deflection—that is 3/10ths of a mg. cm. To use the diagram in Fig. 6 we should have to cut the smallest piece off the point of the tiny pin and suspend that minute piece by the silk thread.

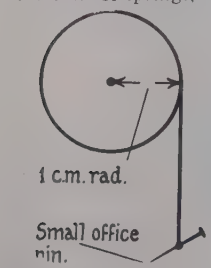


Fig. 6. *Full-scale torque in a pyrometer.*

INSTRUMENT DESIGNER'S PROBLEM

Enough has been said to make evident the problem that the instrument designer had to face when suspensions were to be discarded in favour of pivoted coils. The figures above represent fairly the very small forces which are all the designer has to work with, except in the case of one special class of pyrometer, which will be referred to later. It will now be in order to consider the pivots and jewels themselves.

It will be obvious that it is physically impossible to produce a pivot with an actual geometric conical pivot point, and if it could be made that point would break off or crush as soon as it touched any hard substance for the first time. Finely pointed pivots are often talked about quite freely, even by some persons engaged in actual manufacture or design ; but it is due to loose thinking, because a geometric point has no area at all, and as one cannot carry even the smallest weight on zero area, crushing must result until the deformed point presents an area large enough to carry the load without such a concentration as to cause further crushing.

INTERACTION OF PIVOT AND JEWEL

What is done, therefore, in practice is to make the pivot point as small as practicable and as nearly a spherical surface as can be achieved, somewhat as shown in Fig. 7, though there, for the sake of clearness, the radii of the pivot and jewel are exaggerated compared with their diameters. But we are not yet " out of the wood." The contact between two spherical surfaces of different radii is again an infinitely small surface, and again deformation must result till there is an area large enough to carry the load of the coil and pointer. But here, with a minute spherical point, such an area can be secured by elastic deformation only, and crushing need not result if the workmanship is good and the coil very light.

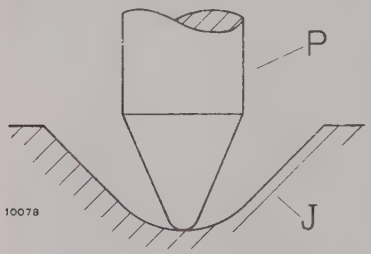


Fig. 7. *Diagram of pivot and jewel.*

So far, so good ; we may consider that, while the instrument is at rest and not subject to any shock or vibration, the minute area of contact between the pivot and jewel is sufficient to carry the load of the coil and pointer without permanent damage. But what happens if the instrument is simply lifted and set down on the bench? The crushing stress on the pivot may be multiplied many times, and, as proof that such effects do take place, it can be stated that it is very rarely that one examines the pivots of a used pyrometer without discovering, under high magnification, some degree of crushing or distortion *unless* the instrument is fitted with elastic cushioning in some satisfactory manner.

EFFECTS OF VERTICAL AXIS

It is necessary here to explain that in all pyrometer indicators, except the special class already mentioned and to be dealt with later, the axis of the coil is arranged approximately vertically. In this way the weight of the coil and pointer is borne symmetrically on one pivot, the other simply serving as a guide to prevent the coil from swinging over sideways. If the pivots are turned outwards, as is more usual with ammeters and voltmeters, the top pivot will fall over and produce rubbing friction which might be too great for the very weak forces in a pyrometer, whereas when in-turned, as in Fig. 5, the coil hangs upon the top pivot and the sideway forces on the bottom pivot can be reduced to practically nothing if the instrument is set up with its axis vertical.

HORIZONTAL AXIS

If the axis is alternatively disposed horizontally, the relative positions of pivot and jewel are as shown in Fig. 8. At first sight it might be thought that, by tightening up the jewels, the pivots could be lifted to the axis of the jewels, but a moment's reflection will show that it would require an infinitely large axial pressure to achieve this, with the inevitable penalty of crushing the pivot. Resting as in Fig. 8, the pivot is virtually a roller of minute diameter and when at rest it will lie at the bottom of the circle of contact in the jewel. But when deflected for instance, clockwise, it will begin to climb up the jewel to the position shown by the dotted circle. When at rest, the weight *W* and the supporting force *S* were vertically in line, but when

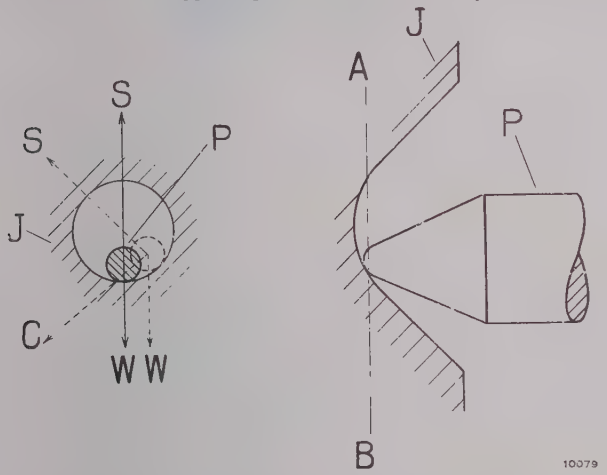


Fig. 8. *Effects of "pivot roll."*

moved to the new position of the dotted circle the weight *W* still acts downwards, but the supporting force *S* acts at an angle, with a resultant force in the direction *C*; thus the weight of the coil adds to the force of the controlling spring in resisting turning. This would not matter if it were always the same, because it could be taken into account in the calibration. But if the instrument is now lightly jarred, the pivot will slip down again to the

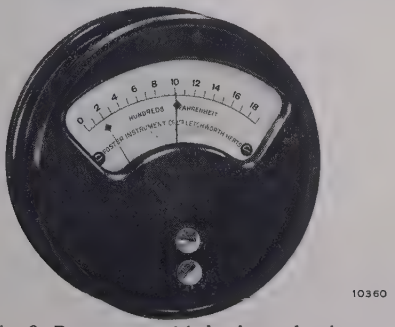


Fig. 9. *Pyrometer with horizontal axis.*

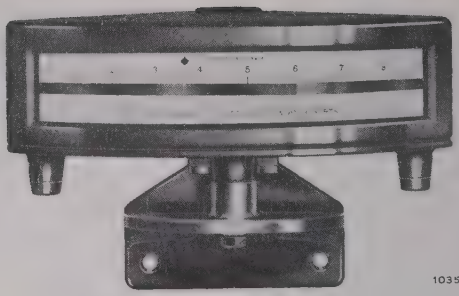


Fig. 10. *Pyrometer with vertical axis.*

bottom of the jewel and the effect of the weight *W* is now abolished. It will be evident therefore that the horizontal axis is suitable only for instruments in which the turning forces and the opposing springs are so strong as to mask the effect of weight. The whole effect is known technically as "pivot roll."

HIGH TORQUE PYROMETERS

In pyrometers used with thermocouples developing relatively large e.m.f., the current that flows can be made large enough to give turning forces sufficient to mask the effects of "pivot roll," provided the external circuit resistances can be kept low and relatively constant. When such high torque instruments were first made as pyrometers, the problem was not properly understood and in order to to allow a large enough current to flow the pyrometer was liable to large errors due to change in the temperature of the instrument itself. Later knowledge has removed these and, for pyrometers used with a single thermocouple and cable of constant length and virtually constant resistance, an instrument with a horizontal axis and a flat scale is possible, with obvious advantages in ease of reading. An example is shown in Fig. 9. Still considering the horizontal axis, it is easy to see that shock or vibration will be even more destructive because a downward shock applies a wedging force between the pivot and jewel, therefore the elastic cushioning foreshadowed above is at least as desirable as in the case of the vertical axis.

SEPARATE SPRINGING OF JEWELS OR PIVOTS

Trouble with damaged pivots was not unknown even in ammeters and voltmeters, notwithstanding their much greater turning forces, and in consequence the spring-jewel arrangement shown in Fig. 11 was produced. In this design the jewels slide in cylindrical housings and are pressed towards the coil by very minute springs. The sliding axial movement is limited by shoulders in the cylindrical housings in order to prevent positive axial "squeezing," which, as already explained, is not permissible. Although of much later date, the design with spring pivots was produced, as shown in Fig. 12. This is essentially the same as that with the spring jewel, except that the weight of the spring and its housing is added to the total load to be carried by the pivots, an undesirable feature though not fatal to the success of the arrangement.

In both of these designs the first downward shock is cushioned and that is so much to the good, but it does involve separation between the other jewel and pivot and on the rebound a partial blow is struck by that pivot on its jewel, though admittedly a cushioned blow. Further, it will be evident that the spring jewel or pivot will experience some amount of sliding friction

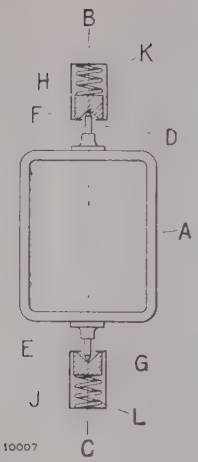


Fig. 11. *Spring-jewel mounting.*

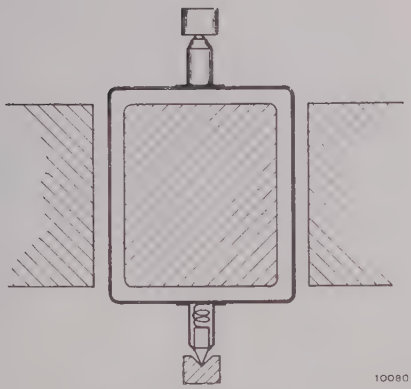


Fig. 12. *Spring-pivot mounting.*

as it gives way under shock. From this fact it will be easy to deduce what is actually found by experiment, namely that as a protection to the pivots of an instrument such as an ammeter, under large single axial shocks, both of these designs achieved considerable success, but when subjected to continuous but small and rapid axial vibrations the inevitable sliding friction limits the motions of the springs, and chattering and damage usually supervene after a short test.

TRANSVERSE SHOCKS

There is, however, a still greater disability suffered by these two arrangements, and by all similar designs which have sliding guides. In transit and in service it is impossible to confine shocks or vibrations to an axial direction: they are just as often transverse to the axis and most frequently in an oblique line. All such devices have no freedom transverse to the axis, and shocks in that direction are the most liable to break off a fine pivot point, or to wear it down by the wedging action already described in relation to a horizontal axis.

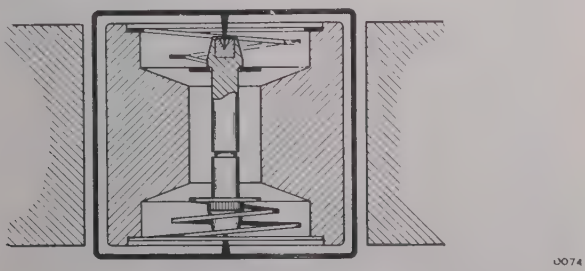
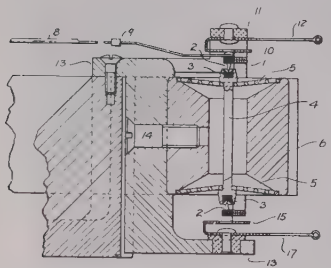
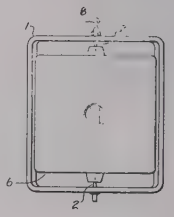


Fig. 13. *Spring mounting with universal cushioning.*

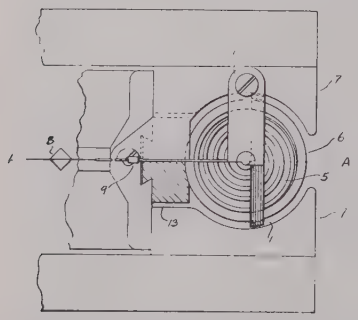
THE RESILIA SPRING MOUNTING



SECTION ON A-A.



ELEVATION OF COIL & CORE UNIT.



10034 PART SECTIONAL PLAN.

Fig. 14.

This patent design is arranged so that it is impossible for the pivot and jewel to be separated and therefore they cannot strike each other in vibration. In the illustration this construction is indicated diagrammatically. A magnetic field is established between the pole pieces of the magnet 7 and the cylindrical iron core 6. The coil 1, carrying the current by means of which the measurement is made, swings in the space between 6 and 7, turning about an axis 4. The coil carries in-turned pivots 2, having their bearings in the conical jewels 3. These jewels are mounted upon a staff 4, which itself is very light and which is held in position relatively to the core 6 by light springs 5. Any jolt of the instrument therefore will move the whole system of coil, pivots, jewels and staff, and it is impossible for the pivots to strike a blow on the jewels. The current to be measured is led into the coil through the control spring 10, and the ligament 15 ; thereafter the circuit is carried by the frame 11 at the top and the insulated arm 17 at the bottom. The zero is controlled by the arm 12. Attached rigidly to the coil is a light pointer 8. The coil 1 is mounted slightly eccentric to the axis 4 so that its weight balances the weight of the pointer 8, a final adjustment of balance being made by the position of the small sliding weight 9. This construction avoids the necessity of the counterweight tail and counterweight usually previously employed, and therefore enables the weight of the whole moving system to be kept to a minimum ; thus the controlling forces may be small and the pivot points very fine and therefore the internal resistance of the instrument can be high without introducing objectionable mechanical delicacy or friction errors. The core 6 is held by the screw 14 to the rigid frame 13, which in turn is attached to the magnet and combines the whole moving system into a unit.

LIMITATIONS OF ACCURACY

A moving coil millivoltmeter type of pyrometer will give accurate and reliable readings over very long periods when used under suitable conditions. There are, however, sources of error which can occur under certain circumstances, some of which are summarized below. These errors are apart from any discrepancy caused by uncompensated variations in the cold junction temperature and which has already been discussed very fully on pages 9-12.

1. Variation in the ohmic resistance of the whole circuit due to temperature changes. The greatest error from this cause is due generally to the copper moving coil and has already been explained on page 20. Less frequently such errors may arise from very long external leads or from long fine wire thermocouples when these are heated over a large portion of their length.

2. Increase in resistance at points of connection between the thermocouple and compensating cable, instrument terminals or switch contacts due either to corrosion or poor mechanical contact.

3. Loss of magnetism—with modern magnetic materials properly aged this is very seldom experienced.

4. Alternation in the torque of the movement control springs which may be due to attack of the spring metal by corrosive atmosphere or to displacement by shock or vibration.

5. Damage to movement pivots by shock or vibration.

In addition, the degree of discrimination in the reading of a moving coil instrument is restricted by reason of the limit of angular deflection and the maximum length of pointer which practical considerations impose. Increasing the pointer length necessitates using a heavier gauge of material to maintain rigidity and heavier counterweights must be added to offset the increased weight. The total weight of the movement is therefore considerably increased and would eventually be such that the pivots could not support it. A scale length of about ten inches is the maximum for an instrument of this class to give satisfactory performance.

Many of these sources of error may be eliminated by using a potentiometric circuit for measuring the e.m.f. generated by the thermocouple. The circuit is described in the following pages.

THE POTENTIOMETRIC CIRCUIT

The method of measuring the e.m.f. of the thermocouple by the potentiometric method is to compare the unknown e.m.f. with a potential of known value in a similar manner that an unknown mass is balanced against known quantities on a chemical or physical balance.

THEORY

A source of e.m.f. such as a battery connected across a resistance wire will create a potential drop (p.d.) along the length of such wire by reason of the current flowing. Provided that the resistance is uniform over its whole length, and the current flowing does not vary, the potential drop between any two points of unit length will be identical and thus subdivisions of the length of the wire may be used as a measure of potential. A simple circuit is shown on Fig. 15. Assuming that the battery potential B is 1500 millivolts, then the p.d. between points Y and Z will be

$$\frac{1500 \times Z_1}{Z_1 + Z_2}$$

If an unknown potential is connected across Z_1 and in opposition no current will flow in the circuit when the potential across Z_1 is equal to the unknown potential. In the event of the opposing potentials not being equal, a current will flow and will be evidenced by the deflection of a galvano-

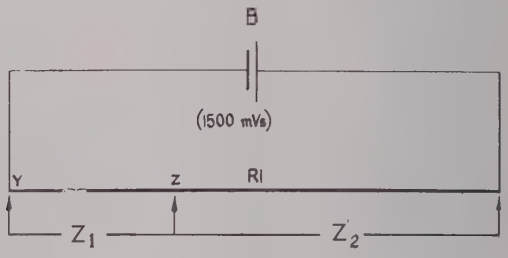


Fig.15.

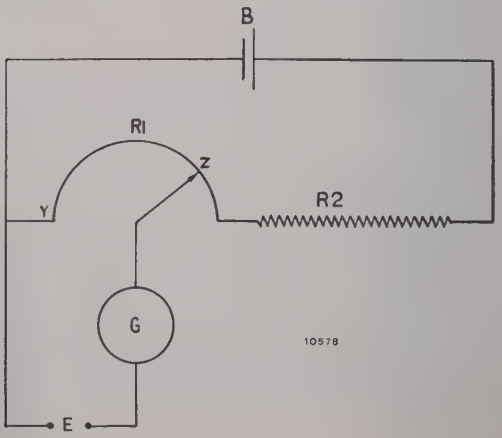


Fig. 16.

meter G in the circuit, as shown on Fig. 16, while the direction of the deflection will indicate whether the unknown potential is higher or lower than that across Z_1. By adjusting the position of Y until no deflection of the galvanometer is obtained the value of the unknown potential may be calculated from the distance YZ.

In practice the resistance wire is usually mounted on the periphery of an insulated drum having a concentrically mounted arm carrying a sliding contact which may be moved to any point on the resistance wire, while a scale graduated in millivolts or equivalent temperature is mounted on the contact arm.

The e.m.f. generated by a Leclanché type battery when new is 1500mV or more, but this will fall to about 1000mV. as the battery approaches the end of its life. As the highest e m.f. generated by a thermocouple does not exceed 70mV., the resistance of the slide wire to the resistance of the total circuit is arranged in proportion. In order to compensate for the gradual fall in the battery e.m.f. a rheostat is incorporated as part of the total resistance, while to ensure that the correct potential drop is maintained across the circuit a Weston Standard cell (which has a definite e.m.f. of 1.018V. at 20°C.) is arranged so that it can be switched into the circuit for comparison purposes. The development of the circuit is now shown below on Fig. 17.

COLD JUNCTION TEMPERATURE COMPENSATION

The e.m.f. generated by a thermocouple depends upon the temperature difference between its hot and cold junctions, and unless the cold junction temperature is maintained at a constant known reference temperature means must be provided -manual or automatic—to compensate for any changes that occur.

In the case of millivoltmeter type instruments the methods usually adopted have already been described on pages 9 to 11, but for instruments incorporating potentiometric forms of measurement the necessary correction is usually effected manually or by means of automatic electrical cold junction compensation as described overleaf.

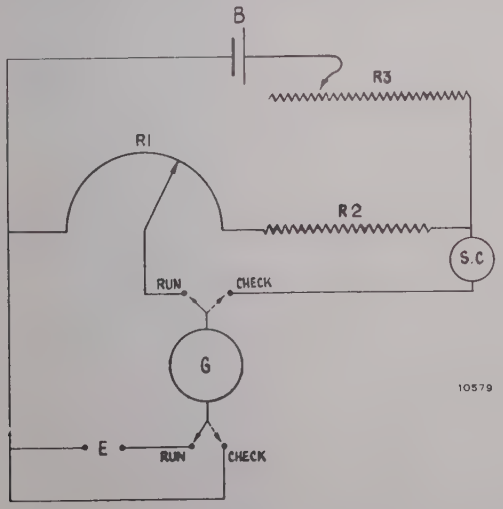


Fig. 17.

MANUAL COMPENSATION

Since the potential drop across the slide wire against which the unknown e.m.f. is to be balanced will be constant between two points Y and Z, shown on Fig. 17 (where Y is at zero potential corresponding to a cold junction temperature of 0°), the thermocouple will be generating a smaller e.m.f. than the interval YZ, and because its cold junction will be at a temperature above 0° it is necessary to subtract from the potential drop between YZ a potential equivalent to that which the thermocouple would develop between 0° and the actual cold junction temperature.

In practice this is done in a simple manner by the use of a second slide wire having a variable contact which is set to an e.m.f. value corresponding to that which the thermocouple would generate between zero and the cold junction temperature. If this value be represented by YJ on Fig. 18 and the thermocouple e.m.f. generated by E, then E = YZ − YJ, thus the known and unknown potentials are equal in value and, being also in opposition as regards polarity, no current will flow through the galvanometer G.

This method of compensation is usually adopted for portable potentiometers which may have millivolt scales or alternatively be supplied with one or more calibrated temperature scales enabling direct temperature measurements to be made on several different types of thermocouple.

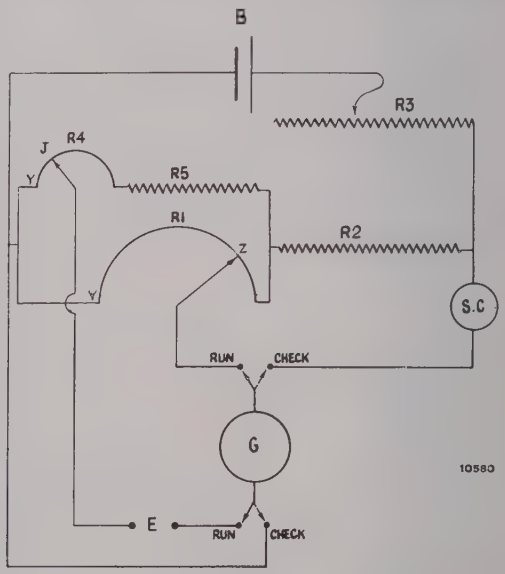


Fig. 18.

AUTOMATIC COLD JUNCTION COMPENSATION

This method is similar in principle to the manual one just described, but differs in that the cold junction slide wire is replaced by a coil of resistance wire having a temperature co-efficient and thus automatically varies its own resistance, and therefore potential drop, in accordance with cold junction temperature changes.

The coil is usually wound from pure nickel wire, which material has a large temperature co-efficient and is connected in series with a high value swamp resistance coil having substantially no temperature co-efficient (R4 and R5 in Fig. 19); this circuit, when energized from a constant potential source, comprises in effect a constant current arrangement, so that the potential drop across nickel coil R4 will vary directly with its resistance.

At zero temperature the nickel coil will still possess appreciable resistance, hence the potential drop across it must be neutralized, and this is achieved by means of resistance R6 positioned in the slide wire circuit, so that at 0° where compensation is not required the two potentials are equal with zero effect on the measuring circuit. The nickel coil and slide wire circuits are connected in parallel, and as the potential drop across this circuit is usually greater than required by the R6 coil and slide wire R1 the surplus voltage is dropped across coil R2.

It follows that the nickel coil must be calibrated to suit the temperature e.m.f. law of the type of thermocouple with which it will be used, and also it must be positioned so that its own temperature and that of the thermocouple cold junction are identical.

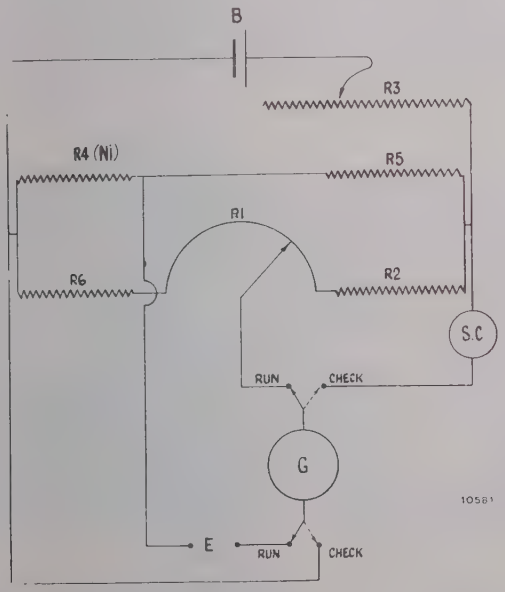


Fig. 19.

CIRCUIT RESISTANCE

It will be appreciated that as no current is flowing in the thermocouple circuit when the potentiometer e.m.f. is balanced against that of the thermocouple, variations in the resistance of the external circuit will have no effect on the accuracy of the readings. A very high resistance in the circuit will affect the sensitivity of the galvanometer, but the effect of this is only to make any small out-of-balance e.m.f. more difficult to detect. There is theoretically no limit to the length which a slide wire may be made and with a very sensitive galvanometer a very close discrimination of the temperature readings is possible, together with a high degree of accuracy.

OPERATION

It is necessary to adjust the position of the contact arm on the slide wire until a balance has been attained in order to take a reading with a potentiometer. For portable instruments, such as that illustrated in Fig. 20, this operation can be carried out manually without difficulty. With a large multipoint installation manual operation would be both slow and inconvenient, while for recording or remotely positioned instruments it would be impossible. Various methods have been devised for automatically repositioning the slide wire contact upon any change occurring in the thermocouple temperature and causing an out-of-balance e.m.f. In general these methods detect the deflection of the galvanometer from its neutral position either by mechanical, photo-electric or electronic means and through the medium of an electric motor the slide wire contact is moved until a new position of balance is reached. The different devices by which this automatic self-balancing is effected are very numerous and therefore it is not possible within the scope of this publication to give more details.

Portable potentiometer for pyrometer testing.

Fig. 20.

ELECTRONIC SELF-BALANCING POTENTIOMETER

A more recent development is the electronic self-balancing potentiometer. With this instrument no galvanometer is used, the out-of-balance e.m.f. being fed to a vibrator with associated transformer, thus producing an alternating voltage. This voltage is amplified and fed to a power valve, the output from which feeds one winding of a two-phase balancing motor. The other winding of the motor is fed directly with A.C. from the supply transformer and acts as the reference phase. Since the phase of the alternating voltage is dependent on the polarity of the out-of-balance e.m.f. the phase relationship between the currents in the two windings of the motor determines the direction of the rotation of the motor rotor. When the system is in balance no e.m.f. is fed to the vibrator and in consequence no A.C. is fed through the output transformer to the motor control winding.

CONSTANT VOLTAGE MAINS UNITS

As already explained, the voltage of the cell supplying the current for the slide wire circuit tends to fall off in use, and in addition it will vary with changes in the ambient temperature. It is necessary therefore to check periodically against the standard cell and, if necessary, adjust rheostat R3. On some self-balancing potentiometers this operation is carried out automatically at regular intervals and also warning may be given when the battery is approaching exhaustion.

It is possible to eliminate the cell altogether as the source of current for the slide wire by using a special constant voltage mains unit. This unit will give a low voltage D.C. output constant to within 0.25% for variations of the mains input voltage up to 10%. Since the normal variations from the nominal mains voltages are seldom as great this, variations in the output voltage to the slide wire are not sufficient to cause any appreciable error in the instrument readings.

1989

1980

Fig. 21.

Electronic continuous-balance circular-chart indicating recorder.

Electronic continuous-balance strip-chart recorder.

OPTICAL AND RADIATION PYROMETERS

It has already been stated in these notes that a thermocouple type of pyrometer can only be used continuously up to a maximum temperature of 1400°C. There are also many instances where, although this temperature limit is not reached, it is not practicable to use a thermocouple because of inaccessibility of the object or because it is not possible to make physical contact under normal working conditions.

In such cases and for all high temperatures beyond the range of a thermocouple pyrometer, an optical or a radiation pyrometer may offer a solution for the measurement of the temperature. Both of these instruments are operated at a distance from the hot body : the optical pyrometer by the intensity of the visible radiation and the radiation pyrometer by the total energy radiated.

Each type of pyrometer has different characteristics and advantages and is suitable for its own particular field of application. The essential distinctions between the two types are tabulated below:

RADIATION

Suitable for temperatures over 500°C. up to 2000°C.

Distance at which receiving tube may be situated from the hot mass is limited and also influenced to some extent by the size of the object.

Cannot be used on objects of small dimensions.

Gives continuous indication of temperature and can be applied to recording and automatic control.

After sighting on to hot mass operation is entirely automatic and no further manual operation is required.

Luminous flame does not affect readings to any material extent.

OPTICAL

Suitable for temperatures over 700°C. up to 3000°C. or higher.

Is not influenced by distance from object.

Can be used to read temperature of very small objects.

Requires sighting and manual operation to obtain reading, and can therefore be used only for isolated readings, and not for continuous indication or recording.

Accuracy affected by luminous flame.

FIXED FOCUS RADIATION PYROMETERS

In all pyrometers of this class the radiant heat such as one feels upon the face when near a hot body is used as the means of measurement.

All bodies radiate heat to their surroundings. Everyone is aware of this fact in relation to any hot body which is very much hotter than its general surroundings, because the heat radiation increases very rapidly with rise in temperature of the radiating body. When it is hot enough (over 500°C.) some of the energy coming from it is visible as light, but there is also other radiated energy of the same nature but of wavelengths too long to be seen by the eye. At temperatures met with in manufacturing processes the energy of the invisible radiation is much greater than that of the visible light. For this reason the Foster fixed focus pyrometer can be made practically automatic, an advantage not attainable with an "optical" instrument, which works only with the visible radiations.

While not attempting to cover the whole general theory of heat radiation, the following notes will show that the design of the Foster fixed focus

pyrometer is in accordance with well-established natural laws. It is well known that light radiations may be collected at a focus by a convex lens or concave mirror. The invisible heat radiations may be concentrated in the same way. The "burning glass" used to focus heat rays from the sun is an example. This power to concentrate the heat received makes possible a radiation pyrometer of convenient dimensions.

HEAT RADIATION LAW

As stated above, the hotter the body the more energy it radiates. The relation between the temperature of the hot body and the energy it gives out is stated in the Stefan-Boltzmann Law, named after the two investigators who arrived at the same conclusion after considering different aspects of the problem.

Mathematically, the law is stated as:

$$E_1 = K\ (T_1^4 - T_0^4)$$

Where E_1 is the energy interchange between a hot body at temperature T_1 and an instrument at temperature T_0. K is constant. The temperatures are absolute, measured from the absolute zero (−273° C.). This law is well founded and has received abundant confirmation, both theoretical and practical. It is used as a basis for the calibration of the pyrometer in the form:

$$\frac{E_1}{E_2} = \frac{T_1^4 - T_0^4}{T_2^4 - T_0^4}$$

For ordinary work the term T_0^4 is negligible compared with T_1^4 or T_2^4 so we may write:

$$\frac{E_1}{E_2} = \left(\frac{T_1}{T_2} \right)^4$$

The law may be stated in words thus: "An increase of one per cent in the absolute temperature of the radiating body results in an increase of four per cent in the energy received by the pyrometer."

The fixed focus pyrometer follows the Stefan-Boltzmann Law very closely. At the same time, as every instrument is calibrated by direct comparison with standards at several temperatures, any small departure from the law is taken into account in the scale and does not produce an error. There are two important practical advantages resulting in an instrument that follows the Stefan Boltzmann Law. Since the energy radiated increases so rapidly with a rise in temperature, the scale is very open at the high temperatures, and this is desirable also because the high temperature cannot be measured by other means. A further advantage is that a change of one per cent in sensibility of the apparatus would result in a change of only one quarter of that percentage in temperature reading.

MIRROR AND LENS TYPE FIXED FOCUS TUBES

There are two types of receiving tubes used with Foster instruments and they are known as the mirror and lens type receiving tubes.

In the mirror type tube the heat rays that fall within the cone of vision of the receiving tube impinge upon a concave mirror and are focused upon a very small thermocouple, which generates an e.m.f. when heated.

In the lens type the heat rays that fall within the field of vision of the lens are focused directly on to a small thermocouple. The heat concentrated upon the thermocouple generates an e.m.f., which may be converted into terms of temperature.

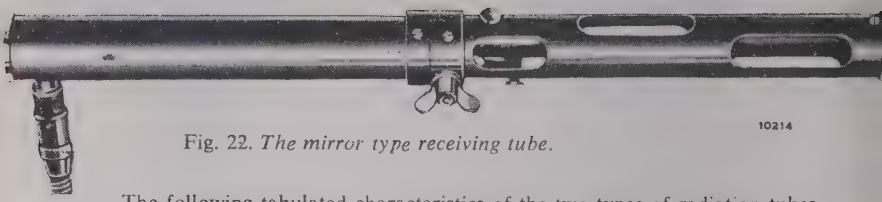


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Fig. 22. *The mirror type receiving tube.*

The following tabulated characteristics of the two types of radiation tubes will be helpful to the prospective user in deciding which type is the most suited to his needs.

MIRROR TYPE	LENS TYPE
Thirty seconds to obtain a steady reading.	Sixty seconds to obtain a steady reading.
Independent of distance within a specified maximum.	Dependent upon distance and size of object.
Length of receiving tube, 24 inches.	Length of receiving tube, 9 inches.
Intended for portable use or for fixed installations where distance and size of hot body cannot be, or are not, accurately known previous to the calibration of the associated instrument.	Intended for fixed use only, particularly in those dirty and hot positions where air-cooled or water-cooled housing is a necessity, and where the distance from hot face to lens, and area of hot face exposed to lens, can be accurately determined.

RECEIVING TUBE—MIRROR TYPE

The tube, which is light and equally convenient either to hold in the hand or to fix in any desired manner, has a diaphragm with an opening at the front end for the entry of the radiant heat from the hot body. Other diaphragms are fitted in the tube to prevent the sensitive part of the instrument at the rear end of the tube from receiving any direct or reflected heat except that which enters correctly through the front diaphragm. The tube is slotted in the front portion to allow the escape of furnace gases, smoke or fumes which may accidentally enter the front diaphragm. A special protection window is fitted for use in dusty situations. For rapid work, particularly under industrial conditions, it is usually quite easy to judge the pointing of the tube by the unaided eye, as the size of the hot body is usually large. To meet those cases where the distance may be large or the hot body small, a special sighting device is incorporated by means of which the user can see the image of the hot body as viewed through the front diaphragm.

CONSTRUCTION OF THE PYROMETER

Simplicity is the keynote of the design. The operation is based on accurately known physical laws, while the arrangement prevents the incursion of practical errors. Fig. 23 shows a diagrammatic section of the receiving tube, approximately to scale. At the front end of the tube *MNPQ* is an aperture *EF*. Radiant heat from the hot body such as *AB* enters the aperture *EF* and is received by the concave mirror *C*. The proportions of the instrument are arranged so that a body *D*, *sensitive* to heat, is where the mirror *C* forms a focused image of the aperture *EF*. If the aperture *EF* could be placed in contact with the hot body, a focused image of the hot body surface, limited by the aperture *EF*, would be formed by the mirror *C* on the sensitive body *D*. This image would not only be a light image, but also a "heat image," and would therefore cause a rise in the

temperature at *D*, depending on the radiant energy given out by the hot body. It is by means of this rise in temperature that the actual measurement is made.

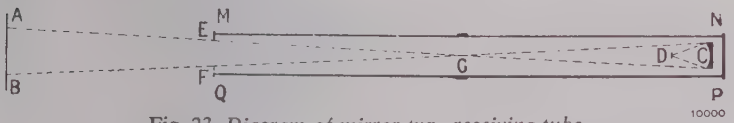


Fig. 23. *Diagram of mirror type receiving tube.*

WORKING DISTANCE

The action of the instrument is independent of the distance from the hot body, provided the hot body fills the cone of vision of the receiving tube. The maximum working distance is given by the following rule. It is a fixed multiple of the size of the opening in the furnace or the hot body outside the furnace. The fixed multiple is called the distance factor. It is 10 for all standard receiving tubes scaled up to 1600°C., and 12 for those scaled to 1800°C. ; e.g. if the peep-hole in the furnace is 3in. diameter and the distance factor of the receiving tube is 10, then the maximum working distance is 30in. from the inner edge of the peep-hole to the centre band on the receiving tube.

CLOSED END TUBES

In cases where it is not possible to have a permanent opening in the furnace wall, a closed-end tube of refractory material is inserted, and the receiving tube attached to the open end. Various modifications of this type of fitting are used. In the illustration shown in Fig. 24 the fixed housing is arranged for water cooling to prevent overheating of the receiving tube.

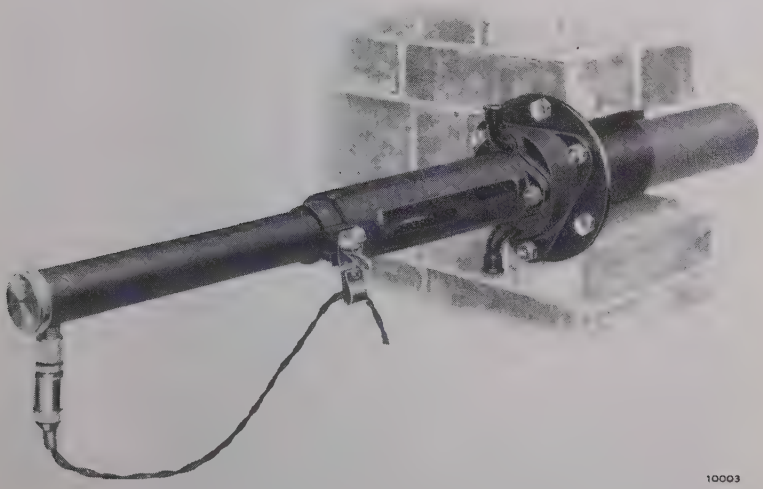


Fig. 24. *Fixed housing in furnace wall, with closed-end tube.*

LENS TYPE FIXED FOCUS RECEIVING TUBE

This type of receiving tube is shorter but of greater diameter and is more compact than the mirror type tube. It is intended for fixed installations only.

The positions of both thermocouple and lens are fixed. The tube is, therefore, of the non-focusing or fixed-focus type. The hot junction of the thermocouple is thus situated at a fixed distance from the optical centre of the lens, and therefore the hot body must be at such a distance from the optical centre of the lens that its image coincides with the position occupied by the hot junction of the thermocouple. This means that the receiving tube must be used at a prescribed distance.

The maximum distance factor is 20—1, i.e. the maximum distance the lens of the tube may be away from the surface of the hot body or the inner edge of the orifice is twenty times the diameter or smallest dimension of the orifice or hot body.

The time taken to obtain a steady reading with the lens type tube is approximately twice that of the mirror type, but as the former is only intended for permanent installation this is no disadvantage.

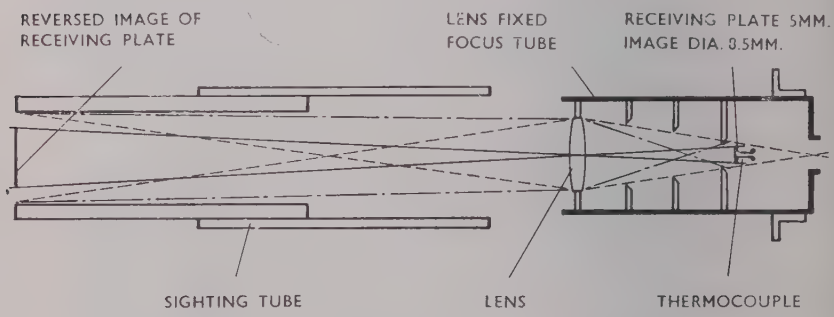


Fig. 25. *Diagram of lens type receiving tube*

HOUSING FOR LENS TYPE TUBE

The receiving tube is completely sealed and airtight so that the sensitive thermal junction and internal connections are protected from dust and corrosive atmospheres. The body of the tube is double-walled, and connections are provided so that air or water may be circulated through the space between the two walls for cooling purposes. Special housings have also been developed for specific applications.

When the temperature to be measured is in a chamber under pressure or vacuum, as in the measurement of the checker temperatures in open-hearth steel furnace regenerators, a special sighting tube is provided which is sealed at the outer end by a mica screen. Air is let into the sighting tube on the furnace side of the screen and builds up pressure at the back end of the sighting tube, protecting it from soot and gases at moments of reversal, etc.

Lens type receiving tubes when used with mica screens have to be specially calibrated for use under these conditions.

The sensitive element of the mirror and the lens type radiation tubes is a small thermocouple of special design which gives a high e.m.f. for small temperature differences. A small copper disc is attached to the hot junction of this thermocouple, on to which the radiant heat is focused, while the

cold junction of the thermocouple is also situated within the radiation tube adjacent to the hot junction, but out of range of the concentrated radiation focused on to the copper disc. As already explained in the section on thermo-electric pyrometers, the magnitude of the e.m.f. generated by a thermocouple depends upon the difference in temperature between the hot and cold junctions. As the temperature of the hot body increases, more radiant energy is emitted and concentrated upon the thermocouple disc, thereby causing an increased temperature difference between the hot and cold junctions. It is obvious, of course, that any variation in the temperature inside the body of the radiation tube will affect the temperature of the cold junction, but as both the hot and cold junctions are in close proximity, any variations in temperature will affect both junctions alike, so that the actual temperature difference is not altered. It is emphasized, however, that the temperature of the tube should not exceed 40°C., and if this temperature is likely to be exceeded provision must be made for air or water cooling or for a special cooling house, as described on page 39.

CONNECTING CABLES

As the cold junction of the thermocouple is situated inside the radiation tube, connection between this and the indicating instrument is made with heavy twin core copper cable. Compensating cable must not be used with a radiation pyrometer.

It is also important to note that the instrument is calibrated for the differential temperature between the hot and cold junctions and therefore there is no correction necessary for the cold junction temperature; the instrument pointer when on open circuit should be set at zero on the scale.

Instruments used with radiation receiving tubes are moving-coil pattern, incorporating the "Resilia" movement, which has already been described on page 28.

CONDITION OF THE HOT BODY SURFACE

The Stefan-Boltzmann Law applies strictly only to radiation from a "black body." The meaning of the term "black body" is a body devoid of reflecting power. Kirchoff, in his study of radiation laws, conceived such a body, one that absorbed all radiations falling upon it. The nearest practical realization is the inside of a uniformly heated space as seen through a small opening. An ordinary furnace viewed through a peep-hole or small door gives a practical realization of Kirchoff's "black body."

"BLACK BODY" RADIATIONS

If the hot body is inside a furnace (or other nearly closed space which is fairly uniformly heated), the radiation coming from it will accord with that from a "black body," and the Stefan-Boltzmann Law will apply. Since the majority of heating processes require the measurement of temperatures inside furnaces, the ordinary calibration of the fixed focus pyrometer is made for these conditions and is known as the "black body" or "furnace" calibration.

On the other hand, if the hot body is out in the open, and its surface has appreciable reflecting power, the radiant energy it gives out will be less than that from a theoretical "black body" at the same temperature. At first glance this consideration appears to put serious limitations upon the radiation pyrometer. Happily this is not so in practice. No matter how large the departure from a true "black body," the energy given out will bear a definite relation to the temperature when conditions as to surface and surroundings are constant. Constancy of condition is usually a necessity in manufacturing processes, therefore the indicator can be specially calibrated to read true temperatures for any defined conditions of use, and this is done successfully in practice.

"BLACK BODY" CORRECTIONS

For temporary use on hot bodies out in the open it is frequently sufficient to add a correction to the reading on the indicator, or, alternatively, to work with the uncorrected reading, since this will serve to secure repetition of any desired temperature. To show the order of magnitude of the correction under different conditions, and to emphasize how small it becomes when the hot body is in even a shallow furnace, the table below is interesting.

Three substances have been taken, namely crucible clay, iron oxide and polished platinum. Each surface has been assumed to be exposed first in the open, next in a shallow recess the depth of which is half the diameter of the opening, and lastly in a deeper enclosure the depth of which is one and a half times the diameter of the opening. The formula used in the calculation is as follows:

$$T_2 - t_2 = t_2 \left(\frac{T_1}{t_1} - 1 \right) \quad \left(\frac{A}{180} \right)^2$$

When T_1 is the true temperature of the hot body (determined experimentally), giving a reading t_1 out in the open, T_2 is the required temperature corresponding to a reading of t_2, $T_2 - t_2$ being therefore the correction to be added to t_2. A is the angle in degrees subtended by the opening of the enclosure from a point on the radiating surface. The temperatures should be absolute, and the difference between T_1 and T_2 not very great. However, the result of applying the formula to a reading t_2 of 1000°C., using the correction based on a reading t_1 of 700°C. does not introduce any objectionable error.

Corrections, in Centigrade degrees, to be added to a reading of 1000°C. when the hot body surface is not under "black body" conditions.

Surface	Out in the open	Recess of depth half its diameter	Recess of depth one and a half times its diameter
Crucible clay	38	10	2
Iron oxide	51	13	2
Platinum	84	21	4

From the above it will be seen that the correction becomes negligible as soon as the hot body is in a heated recess. An ordinary furnace, even with the door wide open, will usually give conditions as good as those in the third case; that is, a recess of depth of one and a half times its diameter. It is therefore clear that no correction is needed in such a case.

From this table it will be seen that the correction for the crucible clay would be to add 4 per cent to the observed reading. This will apply within industrial limits for all firebrick and other refractory surfaces, where they are out in the open, but where they are not glazed.

In the case of iron oxide it will be seen that the correction will be to add 5 per cent to the observed reading, and fortunately this percentage correction applies to all oxidized metal surfaces out in the open, whether they are surfaces of iron, brass, copper or other oxide, and whether the metal is solid or molten, always provided that any non-adherent scale is brushed off. This scale is easily seen, appearing as black patches. The surface of platinum, the third in the table, is more of academic than practical interest.

In the case of a clean stream of molten metal out in the open, and where it is not covered by any skin of oxide, the correction is much larger: in the case of molten iron and steel 33⅓ per cent should be added to the observed reading; in the case of copper, 60 per cent should be added to the observed reading. In these cases care must be taken that the stream

of metal is not clouded with oxide or slag; the receiving tube should be pointed at the stream from one side, close to the spout or, if on top, immediately it has passed a skimming bar. This particular measurement of the stream of molten metal is not an easy one to make, and in practice it is found better to deal with the metal either in the furnace, and therefore as a "black body," or else in the ladle with the oxide surface, but with care the measurement may actually be made upon the clean stream. Owing to the large corrections to be added to the reading it is usually particularly preferable in such a case to have the instrument specially calibrated for a clean stream of molten metal, the particular metal being specified in each case.

In the case of molten glass, the correction is not easily arrived at owing to the partial transparency of glass to heat radiations; but, as an industrial approximation, 10 per cent may be added to the observed reading, provided the depth of molten glass is not less than twelve inches (30cm.). Molten slag varies considerably, but here also, as an industrial approximation, 10 per cent may be added to the reading.

Since the true zero of measurement of the radiation pyrometer is absolute zero (−273°C.), theoretically the percentage corrections should be determined with reference to absolute temperatures. If this were done, of course, the actual percentages would be different from those given above. Fortunately, in practice, this refinement is not necessary. The total range of temperatures dealt with in any particular process, and using any percentage correction, is relatively small, and therefore, basing the percentage on the observed reading, without reference to absolute zero, does not import any error of serious industrial significance.

It should be borne in mind that, given reasonable approximation to true temperature, variations above and below the desired temperature can be observed by the radiation pyrometer with power of close discrimination.

SPECIAL CALIBRATIONS

When working on hot bodies "out in the open," in order to avoid mistakes when the fixed focus radiation pyrometer is used by relatively unskilled operators, it is preferable that the instrument should be specially calibrated for the particular use in view. From the above remarks it will be evident that the indicator of the pyrometer may be calibrated for any particular class of "hot body in the open." The indicator will then be calibrated to give a reading which is higher than the "black body" reading by a percentage equal to the percentage correction indicated above; therefore, by interposing an additional resistance in the circuit, incorporated in the form of a "concentric multiplier," the reading of the indicator may be adjusted for "black body" or "furnace" condition; thus one instrument, by this arrangement, may serve alternatively for two sets of conditions; for instance, "oxide in open" or "furnaces."

While the question of "black body" correction is, from one point of view, a complication in the radiation method of pyrometry, it may be likened to the consideration which has to be given to conduction and depth of insertion when using the thermocouple or other "inserted" type of instrument. The valuable service which can be rendered by a radiation pyrometer upon "hot body" surfaces, as indicated above, gives ample justification for the study of the necessary correction and conditions for accuracy.

OPTICAL PYROMETERS

PRINCIPLE OF OPERATION

The method of measuring temperatures by means of a disappearing-filament type of optical pyrometer is to compare the intensity of the visible radiation emitted by the furnace or object with the radiation emitted from a source of known intensity. The comparison source is provided by an incandescent lamp filament, which is arranged in the field of vision of a telescope through which both the filament and the hot mass are viewed simultaneously. The filament is heated by a battery and the temperature may be varied by means of an adjustable rheostat. The arrangement of the optical system is shown in Fig. 26.

One of the great advantages of the optical pyrometer is that spot temperatures may be obtained, i.e. the temperature of a particular object in the furnace can be ascertained irrespective of the surrounding temperature, provided that luminous flames do not screen or affect the brightness of the object.

Fig. 26. *Optical system of disappearing-filament pyrometer.*

B. Hot mass.
C. Monochromatic screen.
D. Absorption screen.
E. Eyepiece lens.
F. Lamp filament.
O. Objective lens.

USING AN OPTICAL PYROMETER

In operation the object to be measured is sighted through the telescope and the filament thus appears superimposed against the hot mass. The filament then first appears as a dark line against a glowing background, as shown in Fig. 27a. By adjusting the rheostat the temperature of the filament is increased until its brilliance matches that of the object. When this stage is reached the filament becomes invisible against the bright background, in effect it "disappears." If the temperature of the filament is increased beyond this point it will reappear as a bright line and the rheostat must be re-adjusted until it again disappears. The temperature of the lamp filament and consequently that of the hot body is indicated by a moving-coil galvanometer calibrated in terms of temperature.

The monochromatic screen *C* is fitted to the eyepiece in such a manner that it is easily turned in or out of the field of vision. Its function is to eliminate colour difference between the filament and hot body, facilitating matching, and also to prevent dazzle at the higher filament temperatures

a. Too dark b. Too bright c. Correct

Fig. 27. *Filament matching.*

BRIDGE CIRCUIT

The lamp filament is made one of the arms of a Wheatstone bridge and the milliammeter is used as the bridge galvanometer in the manner shown in Fig. 28. The resistances *A*, *C* and *D* are adjusted so that the bridge

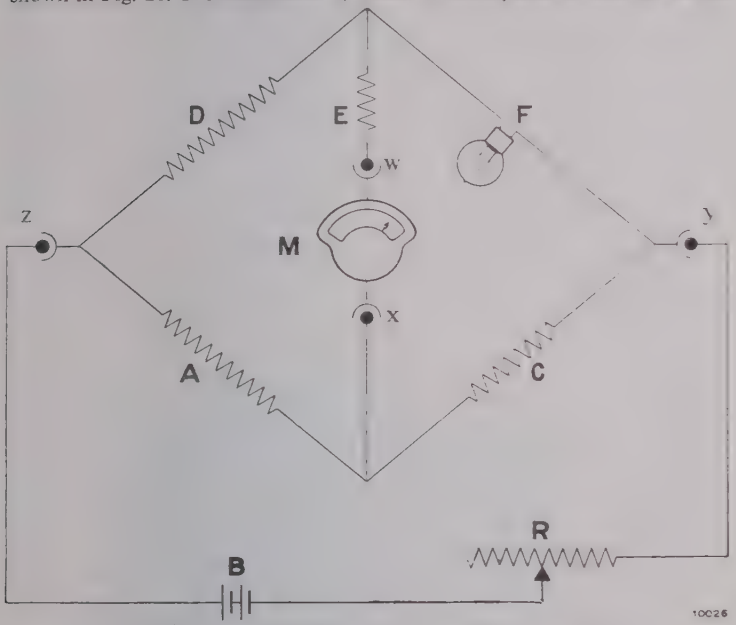


Fig. 28. *Circuit with patent lamp-bridge unit.*

is in balance and the milliammeter *M* is at zero, with no current flowing through it, when the current flowing through the lamp filament *F* is at a predetermined figure, for instance 800°C. As the rheostat *R* is adjusted to increase the current progressively till the filament *F* is at 1600°C. the resistance of the filament will increase. The other resistances *A*, *C* and *D* being of material which does not alter its resistance with change in the current flowing, the bridge will be thrown progressively out of balance, and in consequence an increasing current will flow through the milliammeter *M*, the pointer thus moving up the scale. When calibrating the instrument the "ballast" resistance *E* is put in circuit with *M* so that the pointer moves over the scale for the required temperature range and at the same time so that variation in the temperature of the instrument does not make any appreciable change in its reading for any given current through the lamp. The lamp and resistances *A*, *C*, *D* and *E* are associated in a single unit called the "lamp-bridge unit," which is made detachable from the rest of the system at the points marked *w*, *x*, *y* and *z*. By this arrangement any number of lamp-bridge units may be made interchangeable with a particular milliammeter.

In practice the lamp filament is never run at temperatures higher than 1450°C. so that its calibration remains constant over long periods. An absorption screen interposed between the hot body and the filament will reduce the intensity of the radiation from the hot body. In this way the filament may be matched to a hot mass which is in fact at a considerably

higher temperature than that of the filament itself. In this manner calibrations can be made up to the highest obtainable temperatures without having to overrun the lamp filament.

The telescope, lamp-bridge unit, adjusting rheostat and indicating instrument may be self-contained in a compact unit, or if finer discrimination of the readings is desired a separate portable or fixed indicator having a much longer scale with anti-parallax mirror may be provided.

A source of supply for the current for the lamp-bridge unit is required and this should be preferably a storage battery of the lead-acid or nickel-alkaline type. Dry batteries may be used, particularly where weight is an important consideration. The initial voltage of a dry battery tends to fall rapidly when a current is being drawn from it, so that unless the reading of the indicator is taken immediately the filament has matched, incorrect readings may be obtained due to the fall in voltage between sighting and reading the indicator.

10166

Fig. 29. *Optical pyrometer*

HIGH MAGNIFICATION OPTICAL SYSTEM

The lens system normally fitted to the optical pyrometer has a magnification factor of $\times 1$, the object upon which it is sighted appearing at normal size. For most industrial applications such as measurement of temperatures in large furnaces, gas retorts, coke oven checker work, molten ferrous metals in the stream or the ladle, ingots or billets, open hearth furnace roofs, this arrangement is perfectly satisfactory. Very frequently an optical pyrometer has to be used for the measurement of very small objects at a high temperature for which no other satisfactory methods of measurement are available. Two typical examples are incandescent lamp filaments and very small furnaces for research work. In such cases the very small area of the background on which to sight makes accurate measurement a very difficult matter when using the normal optical system, and for these a special optical system having a high magnification ($\times 3$) can be provided.

It is usually desirable in such cases to have also a tripod or other firm support for the pyrometer in order to facilitate sighting on to the small object.

HOT BODY SURFACE

In using any form of optical pyrometer it is necessary to give a brief consideration to the condition of the surface of the hot body under measurement. The measurement of temperature by any optical pyrometer is a measure of brightness and it is therefore obvious that it is necessary to be sure that the brightness observed is that due to the temperature of the hot body and not to any other illumination. It will be clear that if the hot body is devoid of reflecting power it will emit a brightness truly related to its own temperature and not affected by any extraneous illumination. Consider first a surface in an enclosure such as a furnace, viewed through a relatively small opening. If this furnace were quite cold its surface seen through a peep-hole would appear quite black even though it might be of white firebrick; a moment's inspection will prove this. Such a surface would be known technically as a "black body," and when hot any brightness emitted by it would be accurately a measure of its temperature. For this reason all surfaces inside a furnace that is uniformly heated may be treated as "black bodies," and no further consideration need be given to the nature of their surface.

HOT BODIES IN THE OPEN

Where a surface is out in the open shop, a little further consideration should be given. A surface, for instance, of oxide on a steel billet would look almost black if cold, and have very slight reflecting power, so that, provided it is not directly lighted by any very strong illumination such as sunlight or a very powerful lamp, it can be treated as approximately a "black body." The oxide film formed upon molten metal in the ladle is similar and may also be treated as a "black body." In the case of a stream of molten metal flowing rapidly, any oxide formed upon it will be rapidly broken up, and, for the most part, it will be unoxidized surface that will be observed. If it could be imagined that such a stream of metal were suddenly and completely cooled without any chance to oxidize in the process of solidifying, it would have a bright burnished surface with high reflecting power and, in fact, that reflecting power is there while it is flowing. Under ordinary foundry conditions it will reflect the relatively dark surroundings of the foundry and will therefore appear less bright than a "black body" at the same temperature. For ordinary routine work this effect will be constant and may be neglected; the uncorrected reading serves quite well as a reliable check to control the process.

Where more exact temperature readings are desired for comparison with other measures, the figures already given on pages 42 and 43 under radiation pyrometers will give an indication of the correction to be applied to the observed reading. In the case of a "clean stream" of molten steel, that is a stream flowing so that any oxide formed is rapidly washed away and does not come into the measurement, a reading of 1320 C. on the pyrometer scale will be found to correspond with a true temperature of 1410°C. Thus it will be seen that, in this region of temperature, the observed reading requires the addition of approximately 7%. In the case of molten copper "in the open" a reading of 1025°C. corresponds to a true temperature of 1195°C., that is the correction to be added is larger, approximately 16%.

In all these cases the monochromatic red glass must be used; this is very important on hot bodies "in the open." If the conditions are constant the correction will also be constant, so that, as mentioned above, for routine control the uncorrected reading is equally useful. The above remarks give an indication of the influence of hot body surface "in the open" and it should be noted that this matter is one of definite, well-established physical laws that apply to all types of optical pyrometers.

LOW TEMPERATURE MEASUREMENT

Of the many types of equipment available for measurement of low temperatures, the electrical resistance thermometer is generally acknowledged to be the most satisfactory type for both laboratory and industrial conditions where a high degree of accuracy is called for. Generally the installation is more flexible than with other types as the instrument may, if required, be positioned a considerable distance away from the point of measurement, inter-connection being made by ordinary copper cable. Moreover, several different and widely separated points of measurement can be connected to a single indicating instrument at a central control station. Multi-point recording, or alternative switching from a recorder to an indicator at another control station, is available.

Other advantages of the resistance thermometer may be summarized as follows:

High degree of accuracy.

Very adaptable to suit different methods of application.

The instrument scale can be restricted to cover the working range of temperatures, allowing much closer discrimination in reading.

The sensitive measuring element, connecting leads and indicating instrument are separate units, any one of which, should it become damaged or faulty, can be replaced independently without the necessity of returning the whole installation to the makers for repair.

THEORY OF THE RESISTANCE THERMOMETER

The basic principle of measurement is the variation in the electrical resistance of a conductor of pure metal with any change in its temperature. Pure nickel or pure platinum is usually employed because of the high temperature co-efficients of these metals and their ability to resist oxidization and corrosion. Nickel wound elements are suitable for temperatures from minus 240°C. up to 360°C. Temperatures up to 700°C., or even higher, can be measured with platinum wound thermometers. For the lower ranges, however, nickel is to be preferred, because for a given resistance the conductor is heavier and stronger and also less expensive than platinum.

CONSTRUCTION

The resistance wire is usually wound on to a bobbin or former. Various methods of supporting the windings are available, but in many instances special forms of winding are designed to suit individual applications for which no other method of measurement is as suitable.

In certain cases it is permissible to immerse the winding directly in the medium being measured. This method has the advantage that the element responds almost immediately to temperature changes. Generally, however, some form of protection is necessary. This may be merely a ventilated cover for mechanical protection, as in the measurement of static or low velocity air temperatures, or a completely enclosed and sealed sheath or "bulb" for protection against corrosive or electrically conductive liquids, or against high pressures or abrasive media. Where total enclosure of the sensitive element is necessary, special consideration must be given to thermal inertia and conductivity between the sheath and the winding and also to eliminate errors which may be caused by conduction of heat along the sheath. It is advisable to obtain expert advice in the selection of suitable protection and methods of installation if trouble is to be avoided. As the measuring element is a conductor of considerable length it may be spread over a large area and so measure the average temperature, while on the other hand a thin wire can be wound into a compact space for giving "spot temperatures."

CALIBRATION

Each resistance thermometer winding is individually calibrated and is arranged so that when its temperature is raised from 0°C. to 100°C. the resistance will increase by a definite value. This is known as the fundamental interval or abbreviated "F.I."

It is usual to arrange for the fundamental interval to be in steps of 10 ohms; so that a thermometer element can be calibrated for 10 F.I., 20 F.I., 30 F.I. and so on. 10 F.I. can only be used satisfactorily where the total scale range of the instrument covers not less than 75°C. Where a more open scale reading is required, the element must be calibrated for 20 F.I., 30 F.I. or even higher, according to the particular scale range.

DEVELOPMENT OF THE MEASURING CIRCUIT

The resistance of the thermometer element is measured by the well known Wheatstone bridge method, the basic circuit being shown at *A* on Fig. 30. Resistances R1, R2 and R3 are of fixed values having negligible temperature co-efficient, the thermometer element being connected in the fourth arm of the bridge. The circuit is fed by a battery B, while a galvanometer G is connected across the bridge.

The resistances are adjusted so that the bridge is in balance when the resistance bulb is at the temperature shown at the lower end of the galvanometer scale. There will be no deflection of the galvanometer pointer and it will then indicate the lowest temperature marked on the scale. As the temperature of the bulb increases, and consequently its resistance, the bridge is progressively thrown out of balance and the pointer is deflected over the scale. This deflection is calibrated by means of R5 to read in terms of temperature.

It will be appreciated that with this method of measurement the consistency of the deflection for any particular resistance value of the bulb depends upon a constant voltage being maintained across the bridge. An increase in the voltage will cause a greater deflection and conversely a lower voltage a smaller deflection. The circuit must therefore be modified as shown at *B* by incorporating a rheostat R5 in the battery circuit in order that the voltage applied to the bridge may be adjusted to the correct value.

It is necessary to provide means for verifying that the rheostat is adjusted to give the correct e.m.f. and this is accomplished by substituting a fixed resistance R7 for the thermometer element. The value of this resistance is arranged so that when the e.m.f. is correctly adjusted the instrument pointer will indicate a predetermined value shown by a red mark on the scale.

This method of checking has the advantage that any inconsistency in the galvanometer itself is to some extent compensated for by reason of the comparison between the check resistance and the e.m.f. across the bridge. The installation therefore maintains a very high degree of accuracy.

With the circuit described above, the galvanometer of the indicating or recording instrument is of identical design to that used in conjunction with thermo-electric pyrometers and already described on pages 22 to 28.

VOLTAGE COMPENSATED MOVEMENT

A further development of the resistance thermometer circuit is shown in diagram *D*. With this arrangement, the indications of the galvanometer are not affected by variations in the voltage across the bridge within the limits of plus or minus 10% of the nominal voltage. The galvanometer movement used in this circuit follows very closely the construction of the "Resilia" movement, already described in previous chapters. There are, however, no hair springs controlling the deflection of the galvanometer coil, connection to the coil being made by fine ligaments which do not restrain the deflec-

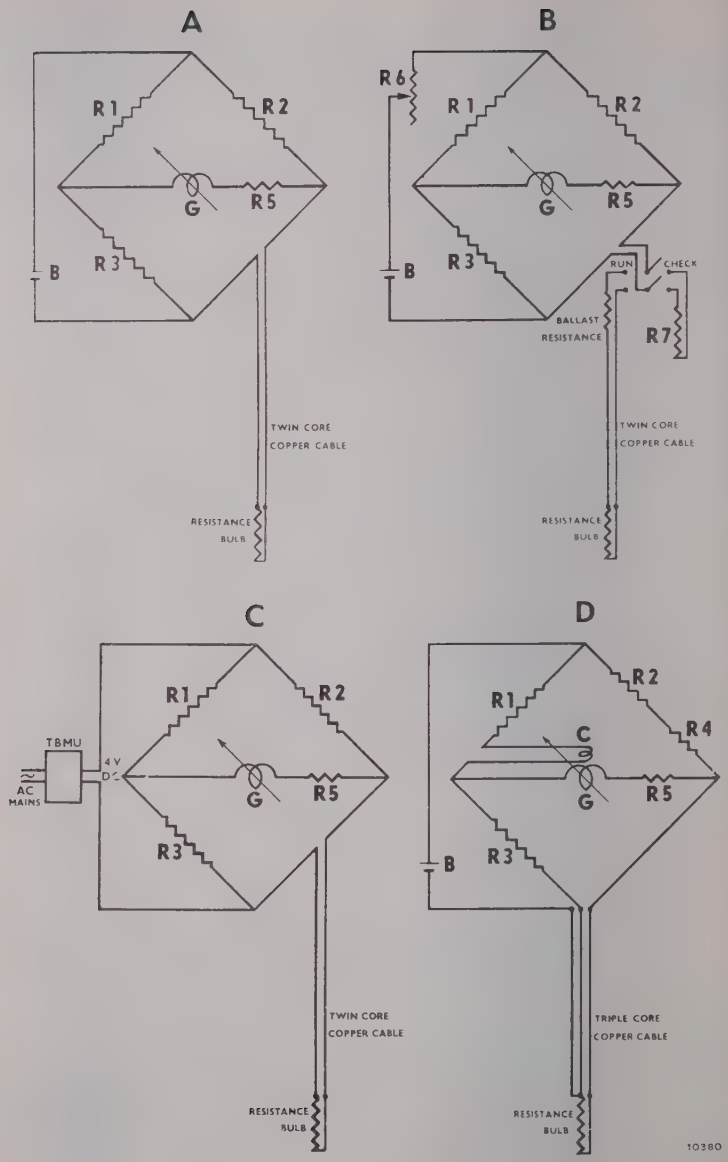


Fig. 30. *Resistance thermometer circuit development.*

tion. In order to provide the opposing torque an auxiliary coil C is wound at each end of the main coil and connected to the bridge circuit as shown at *D* on the diagram. Any variation in the voltage across the bridge, which would influence the current flowing through the galvanometer coil G, affects in like manner the opposing force due to coil C and the deflection can be made independent of variations in the applied e.m.f. No zero adjustment is necessary with this type.

The auxiliary coil C is wound with copper wire, the resistance of which changes with variations in temperature. As this coil is in series with resistance R1 in one arm of the bridge, variations in the resistance of this coil due to temperature change will unbalance the bridge and it is necessary therefore to insert in the opposite arm a coil R4 of copper wire having the same resistance as the control coil C, in order to maintain the balance between these two arms of the bridge.

SCALE GRADUATIONS

The graduations for the non-voltage-compensated movement are practically equal over the whole of the range, while those of the voltage-compensated movement are open at each end of the scale and contracted in the centre. This contraction in the centre of the scale is unavoidable with this type of movement and is a point to be considered when deciding between the merits of the two types.

MAINS SUPPLY UNITS

In the place of a dry cell or accumulator the e.m.f. for the bridge circuit may be supplied from the mains. With a voltage-compensated resistance thermometer this unit comprises a step-down transformer and a rectifier to give a nominal D.C. output of 4.0 volts. The output voltage varies with the fluctuations of the mains voltage, but with a compensated movement normal mains fluctuations do not affect the readings of the instrument.

The above is not suitable for use with an instrument fitted with a non-compensated movement, for which a special type, known as the thermal bridge mains unit, has been developed. The D.C. output of this remains constant within the limits of 0.25% for a variation of ±10% of the specified input voltage. Theoretical circuit embodying a thermal bridge mains unit is shown in diagram *C*.

CONNECTING CABLES

Referring to diagrams *A* and *B*, it will be seen that the connection between the bridge circuit and the resistance bulb is made with twin core copper cable. The resistance of copper cable changes with variation in ambient temperature, and as the whole of this copper cable is in one arm of the bridge it will be appreciated that where the resistance thermometer element is a considerable distance away from the indicating instrument this variation in the resistance can cause an error in the instrument readings. However, if the lead from the battery is connected at the head of the resistance bulb as shown in diagram *D*, each of the two cores will be balanced in opposite arms of the bridge, and the indications of the instrument will thus be independent of any change in resistance due to length of the cable or variations in its temperature.

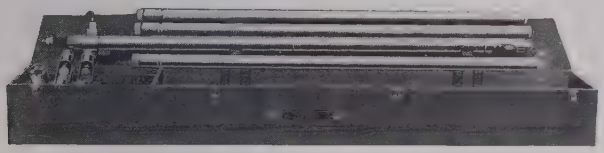
This method of using three-core cable to compensate for variations in the resistance of the connecting leads cannot be used with the circuits shown in diagrams *B* and *C*. It will be seen that the check resistance R7 in diagram *B* is substituted for the resistance thermometer element and its associated cable while checking the battery voltage. As the cable and bulb are completely disconnected from the circuit during the checking period no reading would be obtained if the battery were connected at the thermometer head as shown in diagram *D*.

When using the thermal bridge mains unit shown in diagram *C*, it is not necessary to have a standardizing rheostat and check resistance, since output voltage from the unit is stabilized, but it is necessary that all external circuits should have the same resistance value so that the load on the unit is constant. Instruments using circuit *B* or *C* must be calibrated for a definite external resistance, and it is usual in practice to insert a ballast resistance in each cable circuit by which the external resistances are adjusted to a common value.

FOSTER INTROSCOPES

FOSTER INTROSCOPES are specially constructed optical instruments for examining visually internal surfaces such as bores, tubes, welds, gas bottles, etc., of various shapes and sizes.

They are made in a wide variety of lengths and diameters, jointed and non-jointed, the minimum standard diameter is 3.65mm., maximum lengths vary with the diameters. The largest diameter can be made up to 80ft. effective length. Introscopes from 10.6mm. diameter can be made jointed for convenience in use and transport. Standard diameters of jointed Introscopes are 10.6mm., 12.3mm., 18mm., 24mm. and 34mm.; these sizes can all be fitted with interchangeable viewing heads to give different directions of view and they all have focusing eyepieces. Illumination is by low voltage lamps, usually 6 or 12 volts, self-contained with the Introscope.



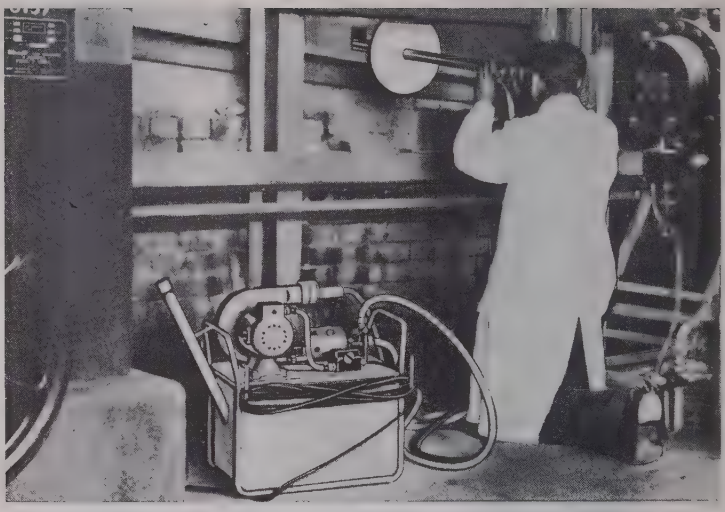
The illustration shows a standard type Introscope 34mm. diameter × 16ft. effective length, operative in four equal lengths of 4ft., 8ft., 12ft. and 16ft., with three viewing heads, fore-oblique, retrograde-oblique and direct-forward.

Introscopes are designed for special applications. Special models are available for the examination of cylinder bores, diesel nozzles, etc. Water cooled Periscopes for furnace viewing are available for observing furnace lining, burner and flame conditions and special Introscopes are also designed for nuclear energy plants where radiation is a hazard. It is generally possible to use Introscopes in conjunction with closed circuit T.V. and adaptors can be made to suit most still and cine cameras.

Fixed wooden centralizing guides or adjustable metal centralizing guides are available for use in large bores.

Portable transformer units are available for use with Introscopes. They are fitted with a rheostat in the secondary circuit to allow variation of light intensity.

Introscopes have over the last 30 years been applied to a great variety of industrial inspection problems. They have been the means of solving the difficulties that so often arise when a "good look inside" is necessary. Foster Instrument Company's long experience is freely available to help solve any special inspection problems and they will design and build any type of Introscope required for any specified application if inspection is at all possible.



Babcock-Foster Portable Periscope

For the better observation and control of Glass melting operations in continuous tank and pot melting furnaces.

SCP/2M/10.64